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Manual for use of Ground Resistivity to Locate Buried Granular Deposits

Using EM 31 and EM 34-3 Instruments

Ontario

Ministry of Transportation

Research and Development Branch

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Manual for use of Ground Resistivity to Locate Buried Granular Deposits — Using EM 31 and EM 34-3

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Abstract:	As part of the study to develop a ground resistivity technique for locating buried granular deposits, a manual for using the EM-31 and EM 34-3 inductive resistivity instruments (by Geonics) was prepared. The choice of instruments depends on the depth of exploration. The manual has guidelines for the various types of surveys and grid orientation for field test sites.
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ME-87-15

Manual for use of Ground Resistivity to Locate Buried Granular Deposits — Using EM 31 and EM 34-3

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MANUAL FORMAT

The investigation methods described in this manual are based on the following two assumptions. Firstly, the study area has been preselected, based on reconnaissance level investigations. Secondly, the personnel using the manual will be familiar with conventional granular material investigation techniques.

As described in this manual, examination of potential buried granular deposits consists of the following three levels of investigation: reconnaissance, preliminary, and detailed.

The reconnaissance investigations may include, but not be limited to, review of regional geological data, airphoto interpretation, evaluation of the water well logs, and discussions with persons familiar with the geological characteristics of the area.

The preliminary investigations consists of a conductivity resistivity surveys along preselected grid lines at relatively wide spacings over potential granular deposits which would be identified during the reconnaissance level investigations. If justified by the resistivity survey results, soil testing would be undertaken at a limited number of sites. Detailed investigations would be conducted on granular deposits which exhibit good potential based on the preliminary investigation.

The detailed investigations consist of conducting resistivity surveys along additional grid lines at relatively closer spacings, and more extensive soil testing and sample analysis program than would be conducted at the preliminary level.

The manual is divided into the four following sections:

Acquisition and Review of Available Data;
Inductive Resistivity Surveys;
Soil Testing and Analysis; and,
Assessment of Granular Resources.

The first section, Acquisition and Review of Available Data, describes the procedure for obtaining additional data for the study area prior to conducting field investigations. The fourth section, Assessment of Granular Resources, explains a method for reviewing the data obtained to determine the quality and quantity of granular material within the study area. The second and third sections, Inductive Resistivity Surveys, and Soil Testing and Analysis, respectively explain the field and data analysis procedures to conduct the preliminary and detailed investigations. To minimize

repetition, the preliminary and detailed investigation procedures are explained in these same sections. However, there is a separate subsection for each, for example:

2.3 Analysis of Inductive Resistivity Survey Data
2.3.1 Preliminary Survey
2.3.2 Detailed Survey.

To clarify the chronological order in which all investigative procedures should be conducted, a Flow Chart is included as Figure 1.

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1. ACQUISITION AND REVIEW OF AVAILABLE DATA

During reconnaissance level investigations, which are conducted to identify a study area, available data such as geology maps and reports, aerial photographs, and water well records should be reviewed. These data should be reviewed on a regional basis to obtain an understanding of the Quaternary geology of the overall area and to identify areas which may contain buried granular deposits.

During the initial stages of the preliminary investigation of a study area, and prior to commencing the resistivity surveys, study-area-specific available data should be reviewed. These data should be related to geology, bedrock geology, perched water table elevations, regional water table elevations, and topographic configuration of the study area. Evaluation of these data will also aid in identifying areas which may contain buried granular deposits. This evaluation process will facilitate selection of the optimum resistivity survey grid configuration.

1.1 Geology and Hydrogeology

Documents such as "The Physiography of Southern Ontario" by L.J. Chapman and D.F. Putnam, and Quaternary geology maps and reports published by the Ontario Geological Survey and the Geological Survey of Canada should be reviewed to determine the Quaternary and bedrock geology, and the glacial and post-glacial history of the area. In addition, Ontario Geological Survey personnel familiar with the area should be contacted to obtain more detailed information about the study area.

Water well records should be obtained for the study area from the Ministry of the Environment. These records contain details of the soil strata and water table conditions. Well records from the Ontario Ministry of the Environment should be examined carefully regarding the geological logic of recording for soil strata and water elevations. These records are prepared by individual drillers, some of whom are more knowledgeable and diligent than others. During analysis of the resistivity survey data, water table information will be useful. If well records cannot be obtained for the study area, records for adjacent lands, if available, can be reviewed to determine general stratigraphic trends in the area.

Ministry of Transportation and Communications documents such as "Granular Material Aggregate Services List" and "Mineral Aggregate Inventory Data Bank" maps and borehole logs should

be obtained, if available, for the study area or adjacent lands. The data usually will provide a further understanding of the geology of the study area and may be helpful in delineating areas suspected of containing buried granular deposits.

1.2 Airphoto Interpretation

The most recent airphotos of the study area can be obtained from the Ministry of Natural Resources at a scale of 1:10,000 or 1:15,840.

Airphoto interpretation should be conducted to delineate areas suspected of containing buried granular deposits and to determine the geological landforms of the study area and environs. The reader should consult an airphoto interpretation manual such as "Airphoto Interpretation of the Physical Environment", by S. J. Glenn Bird and Ian M. Hale, and "Principles of Airphoto Interpretation in Highway Engineering Practice", by B. Sen Mathur and J.F. Gartner, to determine the pattern elements associated with specific landforms, particularly those associated with both surface and buried granular deposits.

The results of the airphoto interpretation would verify and supplement the information obtained in Section 1.1.

1.3 Topographic Data

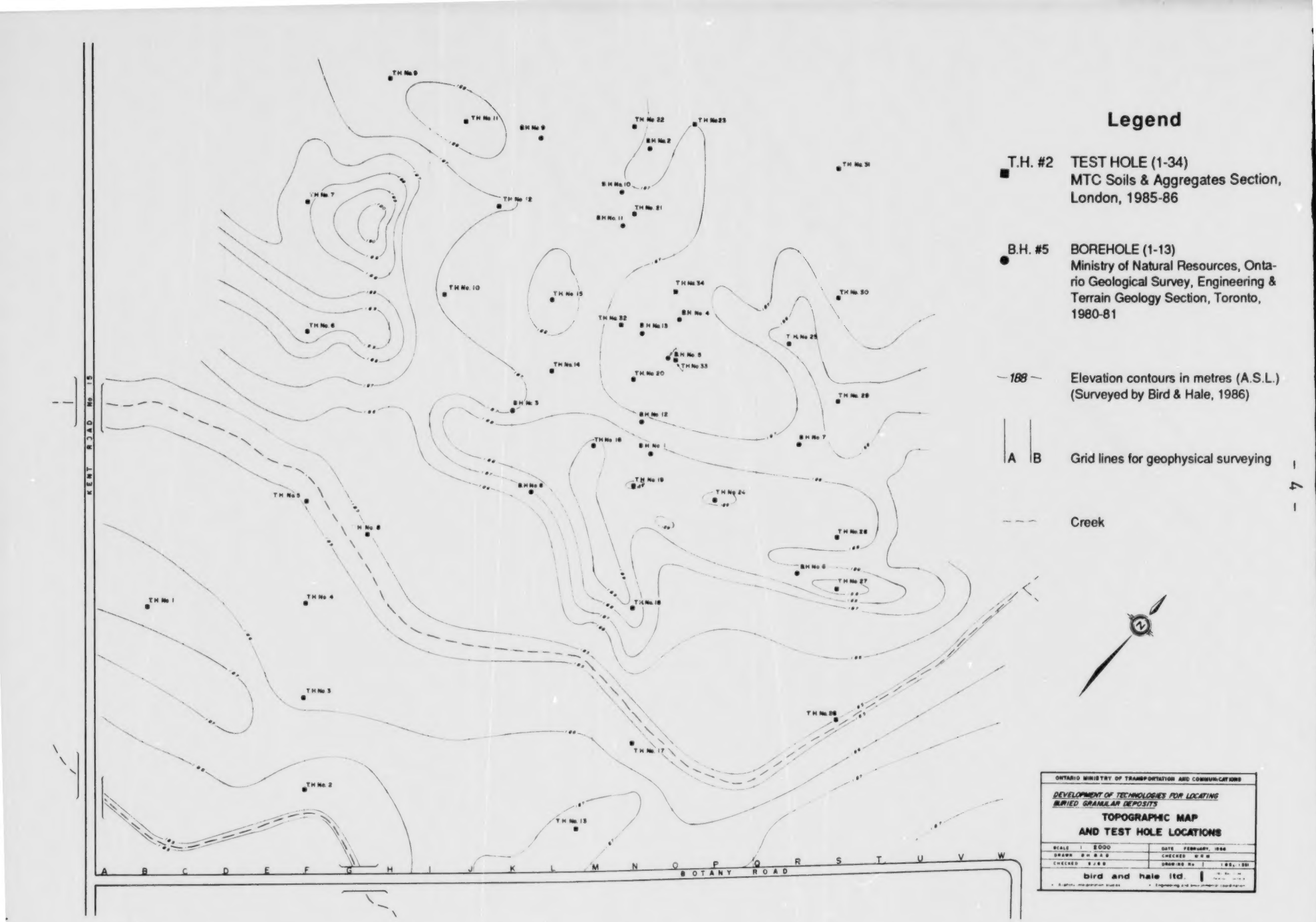
Prior to commencing the preliminary investigation of a study area, available topographic mapping should be obtained. It is preferable to obtain mapping with the largest scale (smallest scale ratio) and the smallest contour interval.

The mapping scale and contour interval varies throughout the province. In some southern portions of the province, Ontario Basic Mapping, having a scale of 1:10,000 and contour interval of 5 m is available. In some northern areas, the most detailed available mapping has a scale of 1:50,000 and contour interval of 7.6 m.

If the results of the preliminary investigation justify further detailed investigation, it may be advisable to obtain more detailed topographic data. Standard surveying methods or photogrammetric techniques may be used to prepare a topographic map. An example of a topographic map, prepared using standard surveying methods, is included as Dwg. No. 1. For smaller areas a sketch map prepared by using the stadia method with a scale of 1 cm = 20 m should also be acceptable. In these cases, landforms should be indicated by slope

directions and angles.

Evaluation of all the information obtained through review of available data, airphoto interpretation, and topographic mapping will facilitate delineation of areas which may contain buried granular material. This information will help determine the optimum resistivity survey grid configuration and orientation.



Legend

- T.H. #2 — TEST HOLE (1-34) MTC Soils & Aggregates Section, London, 1985-86
- B.H. #5 — BOREHOLE (1-13) Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81
- ~188~ — Elevation contours in metres (A.S.L.) (Surveyed by Bird & Hale, 1986)
- A B — Grid lines for geophysical surveying
- Creek

ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS

DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS

TOPOGRAPHIC MAP AND TEST HOLE LOCATIONS

SCALE 1 : 5000	DATE FEBRUARY, 1986
DRAWN B H A S	CHECKED W H H
CHECKED S J A S	DRAWING No. 1 of 1

bird and hale ltd.

2. INDUCTIVE RESISTIVITY SURVEYS

2.1 Design

2.1.1 Preliminary Surveys

2.1.1.1 Choice of Instrumentation

The inductive resistivity instruments described in this manual are the EM 31 and EM 34-3. Both instruments are manufactured by Geonics Ltd.

The choice of instrument to use to survey a specific study area depends on the desired depth of exploration. This will be determined through review of available data, as described in Section 1.

If the granular material is expected to occur within 6 m of the ground surface, then the EM 31 should be used. However, if greater depth of exploration is required, the EM 34-3 is applicable. The depth of exploration with the EM 31 is dependent on the coil configuration. The depth of penetration with the EM 34-3 is dependent on both the coil separation and configuration. These concepts are described briefly below and are illustrated and described in detail in Appendix B.

The coil separation of the EM 31 is fixed and normally it is used in the vertical dipole coil configuration mode. The choice of the coil separation for the EM 34-3 will depend on the depth penetration required. Typically, the horizontal co-planar dipole coil configuration (the coils are vertical and co-planar along the survey line) is used, as this coil configuration is less sensitive to errors introduced by incorrect coil geometry. The use of the horizontal co-planar dipole configuration is encouraged and recommended. If the vertical dipole coil configuration must be used, then extra care should be exercised to ensure that the proper coil geometry (accurate coil separation and co-planar orientation) is achieved. The approximate depths of exploration for the various coil separations and configurations are given below.

Table 1: RELATIONSHIP BETWEEN DEPTH OF EXPLORATION AND INSTRUMENTATION

INSTRUMENT	COIL SEPARATION	VERTICAL CO-PLANAR DIPOLE	HORIZONTAL CO-PLANAR DIPOLE
EM 31	3.7 m (fixed)	6 m-normal position	3 m
EM 34-3	10 m	15 m	7.5 m
EM 34-3	20 m	30 m	15 m
EM 34-3	40 m	60 m	30 m

Vertical co-planar dipole = coils horizontal and co-planar.

Horizontal co-planar dipole = coils vertical and co-planar.

(See Appendix B for clarification)

If the geology of the study area is believed to be complex and the depth to bedrock is greater than 6 m, both the EM 31 and EM 34-3 should be used. Use of both instruments will provide more detailed information and, therefore, a greater understanding of the stratigraphy. The decision for multiple instrumentation depends on the complexity of the geology, level of detail required, and the economic viability specific to each study.

Review of the data during the preliminary investigation may result in a change of instrumentation or use of an additional instrument. For example, if the EM 31 was selected initially, and the preliminary investigation reveal granular material in excess of 6 m below the ground surface, it may be advisable to change to, or resurvey the preliminary grid using the EM 34-3 also.

2.1.1.2 Survey Grid Orientation, Configuration and Station Interval

The objective of the preliminary investigation is to evaluate a potential granular deposit to determine if detailed investigations are justified. Thus, this preliminary analysis facilitates the optimum design of the detailed survey.

The grid orientation and grid line spacing will be determined

through review of available data. For example, if review of available data indicates that buried beach deposits, striking in an east-west direction may occur, the grid lines would be oriented north-south to traverse perpendicular to the suspected formation. If a narrow sinuous feature such as a buried esker is anticipated, then the grid line spacing should be smaller than if a large feature, such as an outwash plain, is expected. This will minimize the possibility of not encountering the deposit.

The preliminary survey lines should be spaced at a distance that will permit their incorporation in a detailed grid. For example, if a detailed grid spacing of 100 m is anticipated, preliminary grid line spacing of 200 m, 300 m, 400 m etc. should be used. A minimum of three lines which traverse areas suspected of containing granular material should be surveyed. These lines should be extended outside of the areas suspected of containing granular material to permit acquisition of background resistivity data for areas which do not contain granular material. The station interval along the lines for a reconnaissance level study would be a maximum of 20 m, for both the EM 31 and EM 34-3.

2.1.2 Detailed Surveys

2.1.2.1 Choice of Instrumentation

The decision to use either the EM 31 or EM 34-3 or both is explained in Section 2.1.1.1.

After the preliminary survey is completed, the results should be reviewed to determine if the correct instrumentation was used. For example, review of available data may have indicated a shallow granular deposit, thus only the EM 31 was used. However, the preliminary investigation may have revealed that the granular deposit is located in excess of 6 m below the ground surface. Therefore, the EM 34-3 also should be used during the detailed survey.

If the preliminary survey reveals that the stratigraphy of the study area is complex, in that the granular material is located at a depth of 15 m below the surface, it may be advisable to operate the EM 34-3 to penetrate to 15 m. The combination of the EM 31 (6 m penetration) and the 15 m and 30 m penetrations with the EM 34-3 would provide a wide range of depth penetrations and facilitate interpretation.

2.1.2.1 Survey Grid Orientation, Configuration and Station Interval

The orientation of the preliminary survey grid is explained in Section 2.1.1.2. The detailed grid should be oriented based on the same principles. The suitability of the orientation of the preliminary grid should provide input to the orientation of the detailed grid. The detailed grid lines should be oriented perpendicular to the strike of major granular-material-bearing landforms such that the maximum number of profiles may be prepared across the landform. It is optimum for the detailed grid lines to be oriented parallel to the preliminary grid lines to permit incorporation of the two surveys. Nevertheless, optimum orientation of the detailed grid should be the controlling factor.

The spacing of the detailed grid lines is dependent upon primarily the expected size of the granular deposit. A line spacing of 50 to 100 m is sufficient for most detailed surveys; however, if a small deposit is anticipated, a line spacing as small as 25 m may be used. Consideration should be given to the minimum size of an economical granular deposit, a study-area-specific concern. The usual practice is initially to use a wide line spacing, such as 100 m. If the desired data are not obtained, additional lines may be surveyed at 50 m spacings. This process may be repeated for narrower spacings if and as necessary. It is common to conduct a detailed investigation for only the portions of the preliminary investigation areas that exhibit potential for granular material.

The station interval is a function of the detail of information required along the survey lines and of the survey line spacing. If the survey lines are located 25 m apart, the survey stations along the lines should be picketed at 10 m or 20 m intervals. The density of observation (station interval) will depend on the instrument used. In the case of an EM 31 survey or an EM 34-3 survey with a 10 m coil separation, the recommended station interval would be 10 m. Hence the lines should be picketed at 10 m intervals. In case of EM 34-3 surveys with 20 m or 40 m coil separation, observations should be made at 20 m intervals. Consequently, the lines should be picketed at every 20 m. If the survey lines are 50 m or 100 m apart, it is suggested that the survey stations should be located at an interval of 20 m along the lines and the observation interval should not be more than 20 m.

2.2 Field Operations

2.2.1 Preliminary Surveys

2.2.1.1 Preparation of the Grid

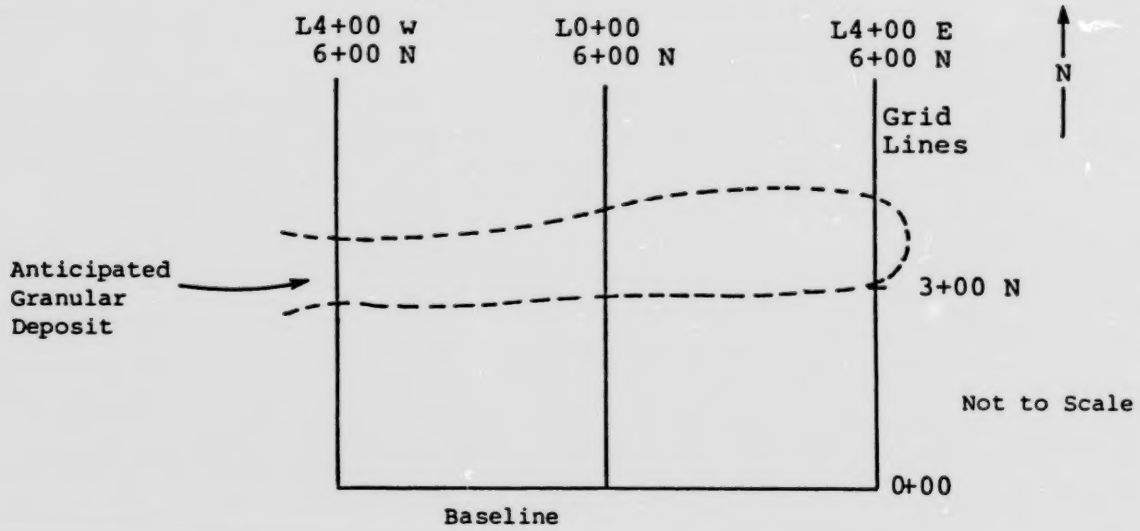
Once the study area has been identified and the specification for the preliminary survey have been established, the grid is laid out in the field. For the majority of preliminary surveys it will be acceptable to establish the grid line and survey station locations using standard compass and chaining techniques. An airphoto background base map is useful as it permits the field crew to check grid line orientation and chainage along the lines, and to correct these if necessary, during the time when the grid lines are compassed and chained. In forested or some cultivated areas, the grid lines and stations may be marked using surveyors' flagging tape. The line and station numbers should be written on the flagging with a waterproof marker. In open areas or where the type of crops will not permit use of flagging, wooden stakes (pickets) may be used to mark the lines and stations. The line and station numbers may be written on the pickets using a lumber pencil or a crayon.

If a greater degree of accuracy is required, the grid may be established using a transit and standard surveying techniques. An overall accuracy of 1:500 to 1:1000 is satisfactory, therefore more sophisticated, time-consuming survey techniques rarely are required.

Figure 2 shows the layout of a typical preliminary resistivity survey grid.

First, the base line is established, approximately parallel to the strike of the anticipated granular deposit. The locations of the grid lines are established and marked when the base line is laid out. The grid lines are then turned off perpendicular to the baseline using a compass, surveyors' prism, or transit. The survey lines are normally identified as east (E), west (W), north (N), or south (S) from the starting point of the grid. In the example in Figure 2, the starting point is in the centre of the grid at station 0+00 and the base line is extended to the east to Line 4+00 E and to the west to Line 4+00 W. This represents a grid line spacing of 400 m. In this example, the stations along the survey lines would be identified as being north of the base line, assuming that the station interval is 20 m. Then the identifications would be 0+00, 0+20N, 0+40N, 0+60N, etc. Thus, every station would have a co-ordinate, for example, (L-400E, 2+40N).

Figure 2: TYPICAL PRELIMINARY RESISTIVITY SURVEY GRID



2.2.1.2 Resistivity Survey Procedures

Prior to departing to the field, the instruments should be checked for proper operation. In addition, the crew should ensure that sufficient batteries, notebooks, pencils, plotting paper, pickets, lumber crayons, flagging tape, inter-connecting cables and instrument-operating manuals are included in the field kit.

On the first page of the field note book the following should be noted:

name of the property;
name of the operator;
the names of the survey crew;
and, instrument type and instrument serial number.

On each page of the notebook, the following should be marked:

(a) coil separation;
(b) coil configuration (HD = horizontal co-planar dipole coil configuration, VD = vertical co-planar dipole coil configuration);
(c) line number;
(d) station number; and,
(e) the instrument readings.

Items (a) and (b) are not needed if the EM 31 is used in its normal survey configuration.

The headings of each page should be:

(1) Transmitter location (Tx);
(2) Receiver location (Rx);
(3) Observation in mmho/m for horizontal dipole (HD);
(4) Observation in mmho/m for vertical dipole (VD); and,
(5) Remarks.

For the EM 34-3 the first two columns show the locations of the Tx and Rx coils using station numbers. For EM 31 surveys, the location at which each observation is made can be indicated in the "Tx" column.

It is important that the locations of features such as roads, buildings, culverts, fences, power lines, creeks, etc., be indicated in the field notes.

Appendix C details the use of an analogue recorder which can be used with the EM 31 to plot continuous conductivity readings along the survey lines. The survey line number, direction of travel, and coil configuration should be noted on the plotting paper. In addition, reading stations should be indicated with a short tick on the plotting paper by zeroing the recorder at each station along the survey line. If the survey lines are long, it is advisable to stop the recorder and mark the station numbers in pencil on the plotting paper every 100 m.

The analogue recorder will provide a higher level of detail, although manual readings at an interval of every 10 m are usually sufficient. The decision to use the analogue recorder will be based primarily on the economic resources of the study, as a two person crew rather than a one person crew is required to perform the survey. It is recommended that the analogue recorder only be used on study areas where vegetation cover is sparse, as dense vegetation will severely impede the progress of the survey.

Operation of the EM 31 and EM 34-3 are not described in this section of the manual; the operating procedures are contained

in the instrument manuals (see Appendix C). However, the following information regarding use of the EM 34-3 should be noted especially. Although the locations of the transmitter and receiver coils are interchangeable, it is advisable to maintain the same relationship throughout the survey. For example, the grid lines may be oriented north-south and the first line may be surveyed starting at the south traveling northerly with the transmitter coil (Tx) leading, and the receiver coil (Rx) trailing. When the first line is completed and the crew moves to the record line, which will likely be surveyed from north to south, the receiver coil (Rx) should be leading. Thus, the transmitter coil (Tx) will still be located north of the receiver coil (Rx).

When taking readings, the long shaft of the EM 31 instrument should be in line with the survey line. Similarly, the EM 34-3 coils should be located along the survey line.

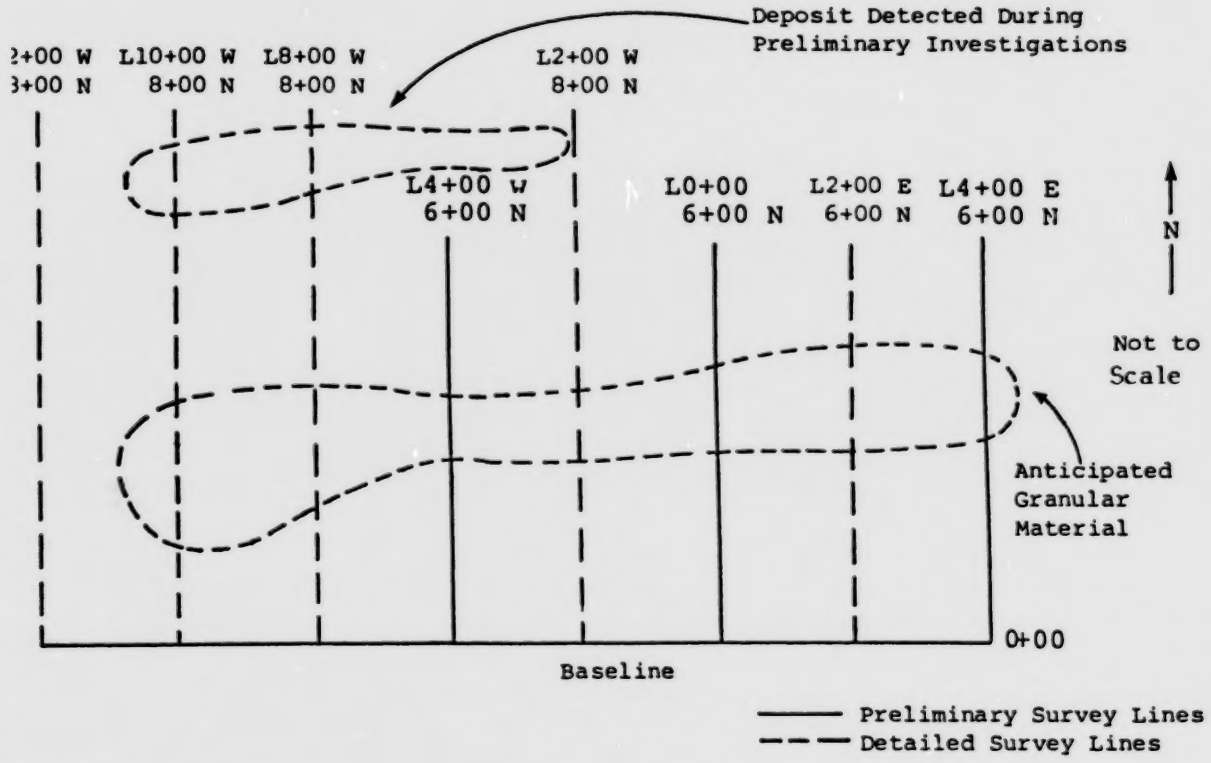
2.2.2 Detailed Surveys

2.2.2.1 Preparation of the Grid

The methods for preparing the preliminary survey grid are explained in Section 2.2.1.1. If the results of the preliminary investigation indicate that detailed investigations are justified, then the preliminary investigation results should be evaluated to permit determination of the optimum detailed grid line spacing. If small and/or discontinuous granular deposits are anticipated, the grid line spacing should be small. If large, continuous deposits are encountered, the grid line spacing may be larger. Normally, additional detailed grid lines at the determined spacing are located between and parallel with the existing preliminary grid lines. In some cases, the detailed grid lines may be extended beyond the preliminary grid lines or additional lines may be added outside of the preliminary grid to cover additional granular deposits or to permit delineation of a deposit. Figure 3 contains a sketch of a typical detailed survey grid which has been developed from the preliminary grid in Figure 2.

If the detailed survey grid is large, it may be advisable to to establish sub base lines (tie-lines) to control the accuracy of the survey grid.

Figure 3: TYPICAL DETAILED RESISTIVITY SURVEY GRID



2.2.2.2 Resistivity Survey Procedures

The EM 31 and EM 34-3 survey procedures are described in Section 2.2.1.2.

The results of the preliminary investigation should be evaluated to ensure that that the optimum instrument, that is EM 31 and/or EM 34-3, is used during the detailed survey as explained in Section 2.1.2.1.

The detailed survey lines should be extended beyond the limits of areas expected to contain granular material until low conductivity readings no longer exist or become sporadic and/or inconsistent.

To evaluate vertical variations of the electrical properties of the ground, it is advisable to survey selected lines with larger (or smaller) coil separations and/or coil

configurations. The additional data will aid in the assessment of the basic data set, and layer thickness and true conductivities can be computed. The survey lines showing the most promising results after completion of the detailed survey may be selected for resurveying at different coil separations or configurations for the reasons explained in Section 2.1.2.1.

2.3 Analysis of Inductive Resistivity Surveys

The application of the inductive resistivity surveying techniques to locate granular materials is based on the premise that the conductivity of dry granular materials (sand and gravel) is less than the conductivity of silts, clays and till which can host the granular deposits. Furthermore, it must be recognized that similar soil types may have different conductivities and that similar conductivities may describe different soil types. Nevertheless, there is a broad correlation between soil types and conductivities, and this correlation can be established when working in a specific area.

To permit an appreciation of the results of inductive resistivity surveys, some basic theoretical concepts need to be discussed. For detailed description of the theory of measurement of terrain conductivity, refer to technical notes by Geonics Limited, "Electrical Conductivity of Soils and Rocks" and "Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers" and the operating manuals for the EM 31 and EM 34-3, (see Appendices A, B, and C respectively).

If the conductivity of the ground is uniform down to the exploration depth of the instrument, then the observed value will be the true conductivity of the ground. That is, if the same conductivity values are obtained by the EM 31 and by the EM 34-3 when the instrument is used with a 20 m coil separation in the horizontal dipole mode, then the observed conductivity is the true conductivity, thus, implying that the electrical properties of the ground remain the same down to a depth of about 15 m below the ground. This in turn, implies that the soil conditions also are similar. The above situation is referred to as the case of the uniform or homogeneous half-space.

In most cases, the earth is stratified and the strata may have differing electrical conductivities. Measurements over stratified earth will yield an apparent conductivity. The observations are always assumed to indicate an apparent conductivity unless known geology would indicate otherwise. The apparent conductivity is a function of the true conductivity, the thickness and depth of the layers, and the

coil separation used.

Figure 6 of Technical Note TN-6 (Appendix B) compares the relative responses for vertical and horizontal dipoles. It shows that the contribution to the apparent conductivity from near-surface materials is very small when the vertical dipole mode is used. Hence this coil configuration is insensitive to changes in very near-surface conductivity. On the other hand, the contribution from the near-surface materials to the apparent conductivity can be larger than those from depth, when the horizontal dipole mode is employed.

One of the advantages of the inductive resistivity measurement is that the apparent conductivity for a multi-layered situation can be calculated simply. These calculations can serve two purposes: (a) they can be used to predict the apparent conductivities for an assumed geological situation; and, (b) the effects of varying the thickness, depth and true conductivity of the layers on the apparent conductivity can be studied. The computations can be carried out using Figure 11 of Technical Note TN-6 (Appendix B), and the equation given below, which is for a four-layer case, but which can be expanded or reduced easily to accommodate the expected number of layers.

The relative contribution from each of the layers can be determined using Figure 11 of Appendix B and the following equation:

$$\sigma_a = \sigma_1[1-R(Z_1)] + \sigma_2[R(Z_1) - R(Z_2)] +$$

$$\sigma_3[R(Z_2) - R(Z_3)] + \sigma_4 R(Z_3)]$$

where:

σ_a - the apparent conductivity

σ_1, σ_2, σ_3, and σ_4 - true conductivity of the layers

Z_1, Z_2 and Z_3 - depth to the top of the second third and fourth layers

$R(Z_1)$, $R(Z_2)$, $R(Z_3)$ - values obtained from Figure 11, Appendix B

The values for R(Z) are taken from the vertical axis of Figure 11, Appendix B, for the appropriate value of Z/s on the horizontal axis. As s, the spacing between the coils in m is 20 m in this case, then for a 3 m thickness of the first layer in this example, Z/s = 3/20 = 0.15. The corresponding value for $R(Z_1)$ is therefore 0.85 as shown on Figure 11. The

total depth of 13 m is used for $R(Z_2)$, thus yielding a value of 0.35.

The following parameters are used:

1st layer: shallow water lacustrine sand: σ_1 = 5 mmho/m
thickness: 3 m

2nd layer: clay and till: σ_2 = 15 mmho/m
thickness: 10 m

3rd layer: sand and gravel: σ_3 = 3 mmho/m
thickness: 4 m

4th layer: till: σ_4 = 15 mmho/m

Coil separation: 20 m

Coil configuration: Horizontal co-planar dipoles

All of the material below ground surface produces 100% of the instrumental response, the apparent conductivity. The material below 3 m contributes 85% of the total response, leaving a contribution of 15% for the first 3 m. The material below 13 m produces 35% of the instrument responses, hence the contribution of the 2nd layer is 50%. The contribution from materials below 17 m is 28%, leaving 7% for contribution from the 3rd layer. The contributions expressed numerically for the above are:

1st layer:	$\sigma_1[1 - R(Z_1)]$	= 5[1 - 0.85]	= 0.75 mmho/m
2nd layer:	$\sigma_2[R(Z_1) - R(Z_2)]$	= 15[0.85 - 0.35]	= 7.5 mmho/m
3rd layer:	$\sigma_3[R(Z_2) - R(Z_3)]$	= 3[0.35 - 0.28]	= 0.21 mmho/m
4th layer:	$\sigma_4[R(Z_3)]$	= 15(0.28)	= 4.2 mmho/m
			---
		hence: σ_a	= 12.66 mmho/m

The above clearly illustrates that the major contribution originates from the two till layers because of their high conductivity. If the third layer, the gravel, is replaced with till, which has the same conductivity as the upper till, then the apparent conductivity will be 15.4 mmho/m. If the upper sand layer is removed and replaced by the upper till, then the apparent conductivity increases to 16.5 mmho/m. These simple calculations show that the introduction of less conductive material will reduce the apparent conductivity.

For the sake of discussion, if the thickness of the third layer, the gravel, is increased to 10 m, and the thickness of the upper till is reduced to 3 m, then the apparent conductivity is reduced to 12.35 mmho/m. The above also indicates that small deviations from the background apparent conductivity of a given area can be significant.

2.3.1 Preliminary Survey

The results of the preliminary inductive resistivity survey(s), using the EM 31 and/or EM 34-3, should be plotted on separate copies of a base map of the study area.

The base maps may be obtained from government agencies such as the Ontario Basic Mapping System and the Ontario Ministry of Natural Resources, at scales of 1:10,000 and 1:15,840 respectively. These maps may be enlarged to a more suitable scale of 1:2,000 to 1:5,000, depending on the size of the study area. The base map will be modified to show the survey lines, stations, planimetric detail such as roads, creeks, power lines, and other cultural features which may influence the evaluation of the resistivity survey data. This map should contain only the necessary data and should not have an airphoto background, as unnecessary detail will complicate interpretation of the data.

Prior to analysis of the survey data, Table 16 of Appendix A, which indicates ranges of resistivity values for various soil and rock types, should be examined. To convert the conductivity readings (mmho/m) obtained with the instruments to resistivity readings (ohm-m) for comparison with the table, divide 1,000 by the conductivity reading in mmho/m.

e.g.,

$$\frac{1000}{16 \text{ mmho/m}} = 62.5 \text{ ohm-m}$$

First, the survey data should be reviewed to determine the levels and variations in conductivity throughout the study area. If the readings are uniform throughout, this indicates that the geology within the depth of penetration of the instrument(s) used is similar across the study area and thus is not complex.

Next the level of the overall conductivity must be examined. If this figure is high, then the conclusion likely would be that either no granular material of significance exists or if it does exist, that the overlying layers of high conductivity material are relatively thick, and would be too costly to

remove. If the overall readings are uniform throughout but are all low conductivity values, this also indicates uniform geological conditions. However, the low value of the readings indicates that granular material probably occurs, and that it may be near the surface. Therefore, the site is likely worthy of further exploration.

If the readings are highly variable along one or more lines, these should be plotted on a plan of the site. The following example, which refers to Dwg. No. 2, helps to explain this preliminary analysis process.

Assume that during the reconnaissance field survey that lines A, E, J, O, T and W were run. This represents a spacing of 240 m between lines.

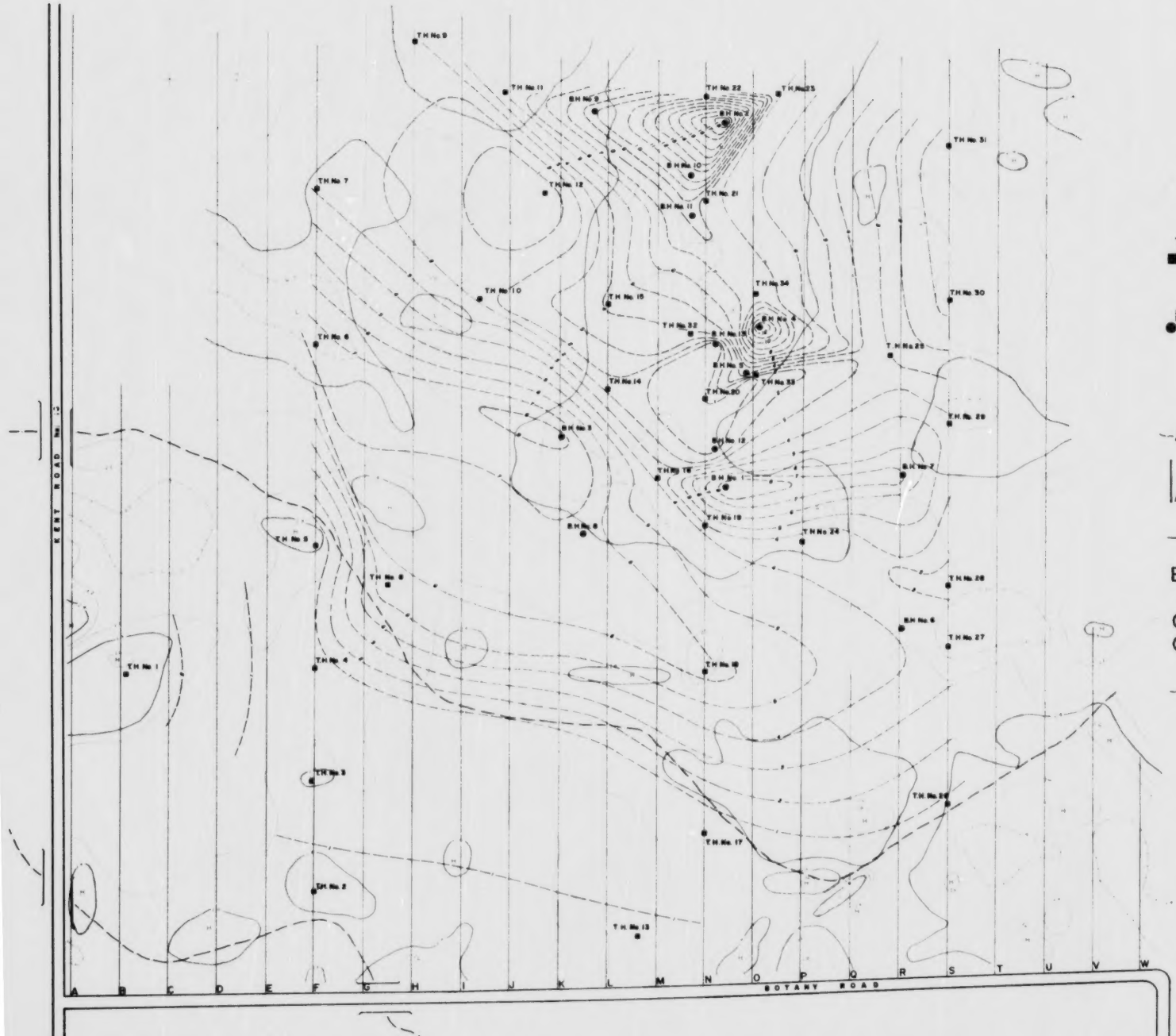
Areas of low conductivity readings should be marked, as well as those having high conductivity, using a different symbol or preferably colour for each. Areas along the individual lines having low conductivity readings in comparison to the background average conductivity of the site are of greater interest, as these represent the areas most likely to be underlain by buried gravel. The planimetric location of these points along the lines is important in this analysis, as it augments the knowledge of the geology of the study area.

Returning to the example on Dwg. No. 2, the following observations would be made, as well as the best locations for preliminary test holes to obtain the most useful information. Selection of the areas for detailed resistivity investigation is also an important objective.

Line A: Conductivity is high relative to the overall area and the variations in readings are small. Therefore, further exploration or location of test holes along this line would have low priority.

Line E: Conductivity is high throughout the southern portion but is significantly lower in a local area of the northern portion. Therefore, test hole locations are warranted, one in the high conductivity area near test hole 4 and two in the low conductivity area in the vicinity of test hole 6.

Line J: High conductivity readings occur throughout with the exception of the north end which is a low conductivity area. The first question to be answered involves the existence of buried gravel in the north portion. Therefore, a test hole should located near test hole 11. The second question involves the possibility of whether the buried gravel in the



Legend

■ T.H. #2 TEST HOLE (1-34)
MTC Soils & Aggregates Section, London, 1985-86

● B.H. #5 BOREHOLE (1-13)
Ministry of Natural Resources, Ontario Geological Survey, Engineering & Terrain Geology Section, Toronto, 1980-81

--2m-- Isopach form lines, 1 m interval (Based on borehole data)

A B Grid lines for geophysical surveying

– – – Creek

EM 34-3

Conductivity in millimhos
Operating height 1 m above ground

—22— Conductivity, 2 millimhos interval

Areas of conductivity low

Areas of conductivity high

ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS

DEVELOPMENT OF TECHNOLOGIES FOR LOCATING BURIED GRANULAR DEPOSITS

SURFICIAL & BURIED GRANULAR MATERIAL
ISOPACH MAP WITH EM 34-3 CONDUCTIVITY CONTOURS

SCALE 1 : 2000 DATE FEBRUARY, 1990
DRAWN B.M.H./B.M. (REVISED 1/91) CHECKED W.B.H.
CHECKED B.J.G.S. DRAWING No 6 (90 - 1990)

bird and hale ltd.

conductivity lows along line E and line J are connected. Therefore, a test hole should be placed midway between these two areas of low conductivity. In this example, as shown on the drawing, the buried gravel is not continuous.

Line O: The high conductivities in the southern half of this line are consistent with the similar results for lines A, E, and J. Thus, a pattern of high conductivities and relatively remote chances of finding buried gravel in the southern portion are being confirmed. The north portion of the line indicates the lowest conductivities of the survey so far and thus requires more investigation. Test holes should be placed near test hole 24, on the conductivity low at bore hole 4, and two other test holes in the low conductivity area such as near test holes 34 and 23.

Line T: The conductivity is high throughout with the exception of low readings in the north centre of the line. Therefore, a test hole should be placed in the vicinity of test holes 27 or 26 to confirm that the material contained in the high conductivity background has not significantly changed from the previous test hole located on Line E. In addition, test holes should be placed in the low conductivity anomaly, near test hole 29, and also in the vicinity of test hole 25. This will serve to confirm the existence of buried gravel in the low conductivity area, as well as whether or not the buried material is continuous between lines O and T. In this example, it is not.

Line W: The high conductivity throughout indicates that the chances of the existence of granular material are remote. No anomalous low readings exist. One test hole should be located in the area of high conductivity shown on the drawing to reaffirm the material types associated with reading. This will also provide a total of three test holes in areas of high conductivity, thus adding a degree of statistical reliability to this preliminary investigation.

2.3.2 Detailed Survey

The decision to proceed to a detailed resistivity survey of all, or more commonly, a portion of the study area is based on the findings of the information collected during the preliminary survey.

Using the same example discussed in Section 2.3.1 and illustrated on Dwg. No. 2, the detailed survey area would be concentrated on each side of Line O, as this area shows the greatest promise for locating buried gravel. The lines should be spaced as previously discussed in this the manual. The lines should be run parallel with the original

reconnaissance lines. They should be continued until low conductivity values either no longer exist or become sporadic and/or inconsistent.

The inductive resistivity data obtained during the detailed survey are plotted to produce contour maps and profiles. The base map described in Section 2.3.1 should be modified to show the survey lines, stations, planimetric detail such as roads, creeks, power lines, and other cultural features which may influence the evaluation of the results obtained at the different coil configurations and coil separations.

2.3.2.1 Conductivity Contour Maps

Separate conductivity contour maps are prepared for each instrument, that is EM 31 and EM 34-3, and if applicable for each survey conducted at a different coil separation and/or coil configuration.

The conductivity readings obtained are plotted on a copy of the base map. For the EM 31, the conductivity readings are obtained at a station and are thus plotted at that station. However, for the EM 34-3, the transmitter coil is located at the station and the receiver coil at the next station along the line when the reading is taken. Therefore the reading is plotted at the mid point between the two stations. After plotting, the data are contoured. The contour interval will depend on the range of values observed, but normally it is 2 mmho/m with larger intervals in areas of steep conductivity gradients. It is suggested that the contouring be done on an overlay on top of the base map containing the conductivity readings. This will permit modification of the contours as needed without interfering with the plotted conductivity readings.

If the conductivity readings are highly variable, resulting in complicated contouring, the following procedure will be of assistance.

- Conductivity profiles should be prepared for selected grid lines, preferably the lines which exhibit the greatest variation in conductivity readings.

- Lines should be selected throughout the detailed survey area.

- The base map containing the conductivity readings should be taped on a light table.

- Profiles, similar to those illustrated on Dwg. No. 3a, that are prepared on transparent overlays, should be

placed on the base map with the datum lines of the profiles aligned along the appropriate grid line. (The procedure for preparing these profiles is described in Section 2.3.2.2.)

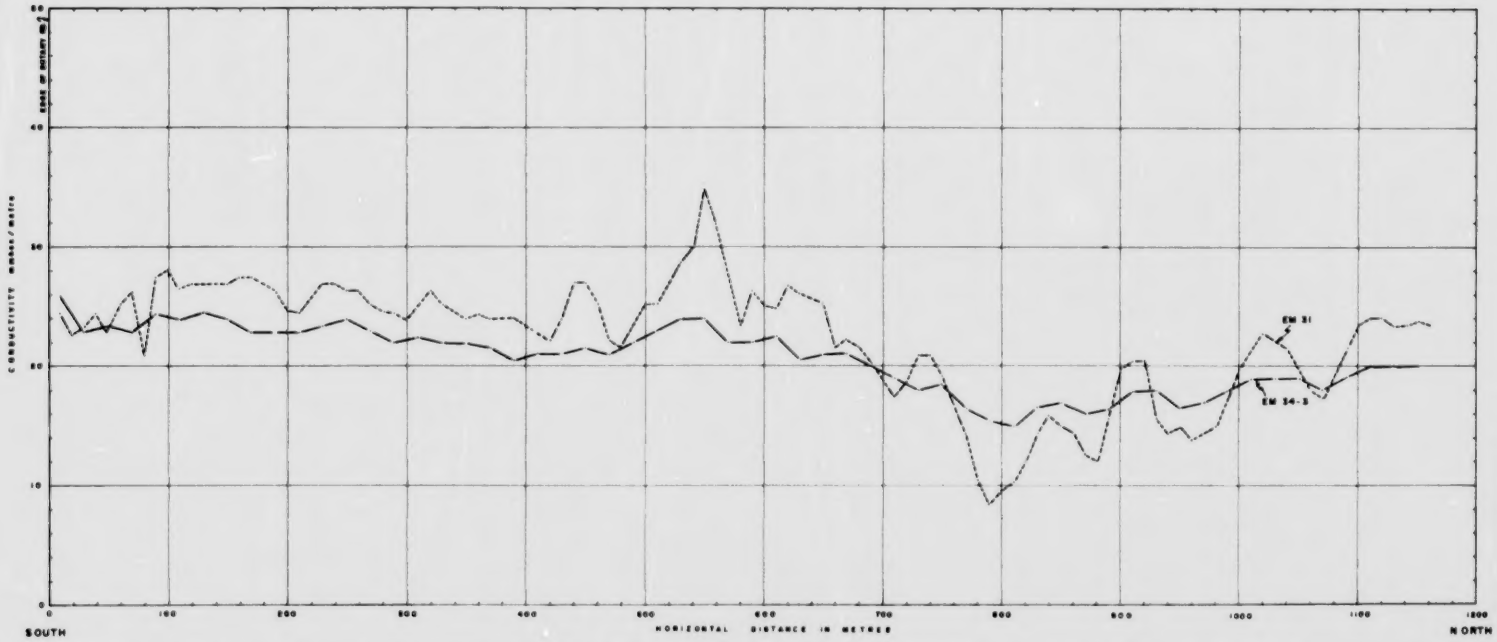
- The overlay, on which the contours will be plotted should then be placed over the profiles. The conductivity profiles will clearly indicate the conductivity lows and highs and provide starting points for the contouring. The conductivity drawings will permit contouring between the lines for which profiles were prepared.

Dwg. No. 2 is an example of a conductivity contour map prepared from EM 34-3 conductivity data. The areas of low and high conductivity have been highlighted.

Decreased apparent conductivity may indicate the introduction of less conductive materials into the geologic section, which could be granular material. Consequently, the object of the evaluation is to locate zones where the apparent conductivity is lower than the apparent conductivities observed in the surrounding area.

The first task in the evaluation of the survey data is the correlation of known geology, from surface observations and available data, with the apparent conductivity map. This correlation can provide some ideas about the relationship between the observed conductivities and soil types. These relationships can be the fundamental information upon which the evaluation is built. If geologic data are lacking, then evaluation has to be based on general principles. Following the correlation between known geology and conductivity data, the apparent conductivity contour maps are studied with the objective of outlining areas where the background apparent conductivities are relatively uniform, thus reflecting uniform geologic conditions. Departures from the background, such as zones of lower apparent conductivity, indicate that the geologic section is different. The significance of an anomalously low conductivity area is enhanced as the difference between the background apparent conductivity and the apparent conductivity of the anomalous low increases. Larger difference can indicate that the less conductive material (potential granular material) is thicker and/or shallower, and/or that the material is less conductive than in areas where the difference is smaller. The zones of larger difference will constitute prime drilling locations.

When an area is surveyed using two instruments of differing depth penetration, or the surveys have been conducted using



Legend

EM 34-3
Operating horizontal dipole mode
Coil separation 20 m

EM 31
Operating vertical dipole mode
Reading taken at 10 m interval

ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS

DEVELOPMENT OF TECHNIQUES FOR LOCATING BURIED GRANULAR DEPOSITS

CONDUCTIVITY PROFILE
GRID LINE 'F'

SCALE HOR. 1" = 200'	DATE FEBRUARY, 1968
VERT. 1" = 200'	DRAWN A.D.
CHECKED W.R.H.	DRAWING No. 5a 100 - 1061

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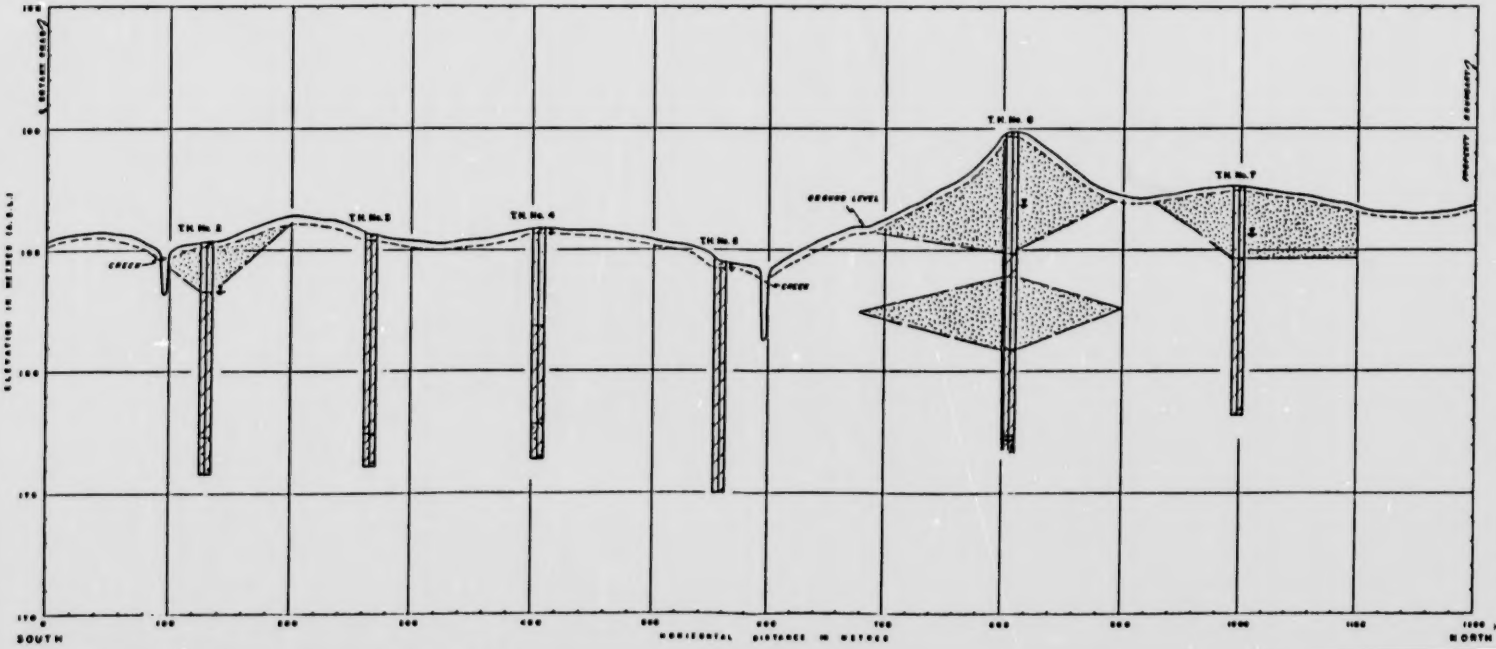


SOIL STRATA SYMBOLS

- ORGANICS or TOP SOIL
- GLACIAL TILLS (Cohesive)
- CLAYS
- CLAYS & SILTS
- SANDS
- SANDS & SILTS
- GRAVELS
- SANDS & GRAVELS
- SILTS
- WATER TABLE

INDICATES ONE OR COMBINATION OF THE FOLLOWING: SANDS, SANDS & SILTS, GRAVELS, SANDS & GRAVELS

ONTARIO MINISTRY OF TRANSPORTATION AND COMMUNICATIONS

DEVELOPMENT OF TECHNIQUES FOR LOCATING BURIED GRANULAR DEPOSITS

TOPOGRAPHIC AND SOIL PROFILE
GRID LINE 'F'

SCALE HOR. 1" = 200'	DATE FEBRUARY, 1968
VERT. 1" = 100'	DRAWN A.D.
CHECKED W.R.H.	DRAWING No. 5b 100 - 1061

bird and hale ltd.

two coil separations and/or coil configurations, very useful data are obtained. The comparison of the contour maps will reveal the variation of conductivity with depth. For example, a conductivity low which only occurs on the shallow penetration map indicates that the low conductivity material is shallow. If low apparent conductivities are observed on both the shallow and deep penetration maps, the combination would suggest that the low conductivity material extends to depth. If the low conductivity zone appears only on the deeper penetration map, then the implication is that the low conductivity material (e.g., granular material) is at some depth covered by material with higher conductivity.

2.3.2.2 Conductivity Profiles

The results of the resistivity surveys can also be presented as profiles, such as those illustrated in Drawing No. 3a.

As discussed previously, it is advantageous to prepare the profiles at the same horizontal scale as the base map. This permits overlaying the profiles on the base map which facilitates contouring of the conductivity data, as described in Section 2.3.2.1. The details of profile line location and orientation should be shown.

Presentation of the conductivity data in profile form is very useful when the survey has been conducted with more than one instrument (EM 31 and EM 34-3), or with more than one coil separation or coil configuration (e.g., horizontal dipole survey with 10 m and 20 m coil separation, or 20 m coil separation horizontal dipole and 20 m coil separation vertical dipole survey). The advantage of viewing the conductivity data in profile form is that the relationship between conductivities obtained by instruments of differing depth penetration and/or by using different coil configuration and/or employing different coil separations are easily recognized. If, at a station, the observed apparent conductivities are the same, then this infers that the conductivities remain similar with depth. Consequently, the soil section is probably quite uniform at this location. If the profile of conductivity obtained by the shallower penetration instrument is above the profile conductivity produced by the deeper penetrating instrument, the implication is that a more conductive upper layer overlies a less conductive material. If the profile of conductivity of the shallow penetration instrument is below the profile of the deeper penetrating instrument, this intimates that less conductive material overlies more conductive soil types.

Profiles of the topographic and soil data obtained by surveying and drilling may be plotted in profile form on the

same sheet as the conductivity profiles (see Drawing No.3b). The presentation of the results in this combined profile form facilitates the evaluation of the correlation between the geoelectric data and geology. Comparison of the topographic and soil data and the conductivities could reveal new factors which can form the basis of re-evaluating the contour maps. This re-evaluation may result in the identification of additional soil testing sites.

3. SOIL TESTING AND ANALYSIS PROGRAMS

3.1 Selection of Test Hole Locations

3.1.1 Preliminary Survey

The results of the preliminary resistivity survey(s), plotted as described in Section 2.3.1, should be evaluated to select a minimum of three soil test locations. Available geological data also should be evaluated during selection of the soil test sites.

The objective of the preliminary investigation involves the decision regarding undertaking further detailed surveys of the study area. This will be based on the occurrence of the required type of granular material within the study area. As previously described, generally granular material is indicated by low conductivity readings. Therefore, soil test sites should be located in the area of lowest conductivity. If the budget permits, it would be advantageous to conduct soil tests in the areas of medium and high conductivity readings to determine the soil conditions that occur in these areas.

The conductivity readings should be plotted on the base map along the survey lines. However, it is not necessary and may not be advantageous to conduct all of the soil investigations along these lines. For example, if low conductivity readings are obtained in approximately the same locations on adjacent lines, it may be advisable to conduct a soil investigation between the lines to determine if the anomaly is continuous.

3.1.2 Detailed Survey

The conductivity contour map(s), geological data, and results of the preliminary investigations should be reviewed to select a minimum of three survey lines which:

(1) contain both high and low anomalies; and,

(2) are representative of the various terrain and geoelectric conditions present in the study area.

If possible, the lines selected should be approximately evenly spaced across the study area.

Each line should contain a minimum of:

(1) Three test holes in areas of low conductivity to

confirm the presence, and evaluate the quality and quantity, of buried granular deposits.

(2) One test hole in an area of middle conductivity to determine if the granular deposit extends into these areas and, if so, the existing conditions which produce higher conductivities than those normally expected. For example, such conditions as a higher water table or a thinner seam of granulars could prevail.

(3) One test hole in an area of conductivity high to confirm the presence of non-granular material and to determine what soil and water table conditions are present in these areas.

In the event that lines selected for the detailed soil investigations have been surveyed previously, at the preliminary level, any soil tests conducted in areas meeting the required conductivity can be used instead of testing additional sites.

3.2 Soil Testing and Sample Acquisition

3.2.1 Preliminary Survey

It is recommended that soil testing be conducted to the penetration depth of the resistivity instrument used or to bedrock, whichever is less. If this is not practical, the maximum penetration depth of the testing equipment should be used. In most cases the penetration depths of the resistivity instruments will necessitate the use of a drill for soil testing. However, in some cases, the equipment and/or the budget may not be available. If the depth of the granular material is anticipated to be shallow, the use of a backhoe will be more effective in obtaining samples and usually will be more economical.

Soil strata should be logged using the Ministry of Transportation and Communications soil classification method.

Changes in soil moisture content and the elevation of the groundwater table should be noted. Minor changes in the silt and clay content, particularly in the granular material, should be noted as these contents may have a major influence on the conductivity readings.

Twenty kilogram samples of sandy soil and thirty kilogram samples of coarse granular material strata should be obtained for laboratory analysis. If the budget permits, it would be advantageous to obtain samples of the major non granular strata for analysis, as well as for verification of fine

grained soil types and moisture contents.

3.2.2 Detailed Survey

The soil testing and sampling procedures used during the detailed investigations are similar to those used during the preliminary investigation.

The results of the preliminary investigation may permit modification of the testing procedures used during the detailed investigation. For example, if the preliminary investigation reveals that the granular material is shallow, it may be more appropriate to use a backhoe rather than a drill for the detailed investigations and vice versa.

3.3 Analysis of Soil Test Data

3.3.1 Preliminary Survey

3.3.1.1 Laboratory Analysis of Soil Samples

Granular material samples obtained during the soil testing should be analyzed in a soils laboratory to evaluate its suitability as aggregate. This would be determined by comparing the test results to the required specifications for aggregates as set out by the Ministry of Transportation and Communications.

Usually, a sieve analysis will be sufficient to determine the initial suitability of granular materials for aggregates. Additional tests, such as petrographic analysis and abrasion tests, are usually required to evaluate the suitability of the material for various uses.

3.3.1.2 Plotting and Analysis

Usually the results of soil testing conducted during the preliminary investigations are plotted in the form of individual logs. The logs are then evaluated to determine the occurrence of granular material.

If a sufficient number of sites are investigated and the locations of the sites are appropriate, a soil section may be prepared (see Dwg. No. 3b). Evaluation of the profiles will be of assistance in determining the geology of the site.

3.3.2 Detailed Survey

3.3.2.1 Laboratory Analysis of Soil Samples

The analysis procedures used will be similar to those used during the preliminary investigations. However, during the detailed investigations, the degree of confidence will be higher that granular extraction will occur. Therefore, it may be appropriate to conduct a wider range of tests on a greater frequency of samples.

3.3.2.2 Soil, Groundwater and Topographic Profiles

Topographic profiles should be plotted on separate sheets for those survey lines containing test holes (see Dwg. No. 3b). This can be done by plotting elevations versus distance along the survey lines, both parameters being extrapolated from the topographic map of the site.

The locations and logs of test holes are indicated on the profile, and the soil strata and water table data are plotted using the standard Ministry of Transportation and Communications soil legend.

These data then may be interpreted to prepare stratigraphic sections of the study area.

3.3.2.3 Granular Material Isopach Maps

The locations of the test pit sites, from both the preliminary and detailed levels of investigation, should be plotted on a base map of the study area. The thickness of granular material that occurs at each site are plotted adjacent to each location. An isopach map, which indicates the thickness of granular material, then may be prepared (see Dwg. No. 2). An individual isopach map may be prepared for different granular material strata, for example, one map for the surficial material, and one map for buried granular material.

Granular material plotted on isopach maps will include sands, gravels and combinations thereof and, depending on the intended use, granular materials plotted may have to meet or be capable of meeting through processing, certain specifications such as those set out by the Ministry of Transportation and Communications for granular "A", granular "B", etc.

In general, isopach contours are produced by interpolating the depths of granular materials between test holes. It

should be noted that the accuracy of isopach contours decreases as the distance between these holes increases. Therefore, contours between holes greater than 100 m apart should not be relied upon too heavily for delineating areas of various depths of granular materials.

Contours should be left open in areas where sufficient test hole data do not exist.

The isopach maps should be produced on an overlay at the same scale as the conductivity contour maps.

If only one resistivity instrument has been used for the investigation, an isopach map should be prepared based on the total cumulative depth of granular material noted at each test hole, as illustrated in Dwg. No. 2. It should be noted that any strata deeper than the penetration depth of the instrument should be included and also noted separately for ease of analysis of the results.

If more than one instrument, coil separation or coil configuration have been used, an isopach map should be prepared for each case, detailing the total cumulative depth of granular material down to the penetration depth of the instrument used. For example, if the EM 31 was used in the vertical dipole mode and the EM 34-3 was used in the horizontal dipole mode with a coil separation of 20m, isopach maps would be prepared to depths of 6 m and 15 m respectively.

The isopach maps are to be overlaid on their respective conductivity contour maps and analyzed, to determine general correlations between conductivity readings and depths of granular material. This will facilitate further delineation of areas with probable granular deposits.

4. ASSESSMENT OF GRANULAR RESOURCES

The data obtained from the laboratory analysis and the granular material isopach maps should be reviewed to determine the quality and approximate quantity of granular materials available.

In determining the approximate quantity of granular material, areas which exhibit similar conductivities to those outlined by isopach contours can be assumed to contain approximately the same depth of material.

Based on the quality and estimated quantity of granular material available, the agency conducting the survey will decide whether the deposit is economically viable for aggregate production. If so, further investigations may be advisable to determine the extent of the deposit to prepare an estimate of the quantity and quality of granular material available for various uses.

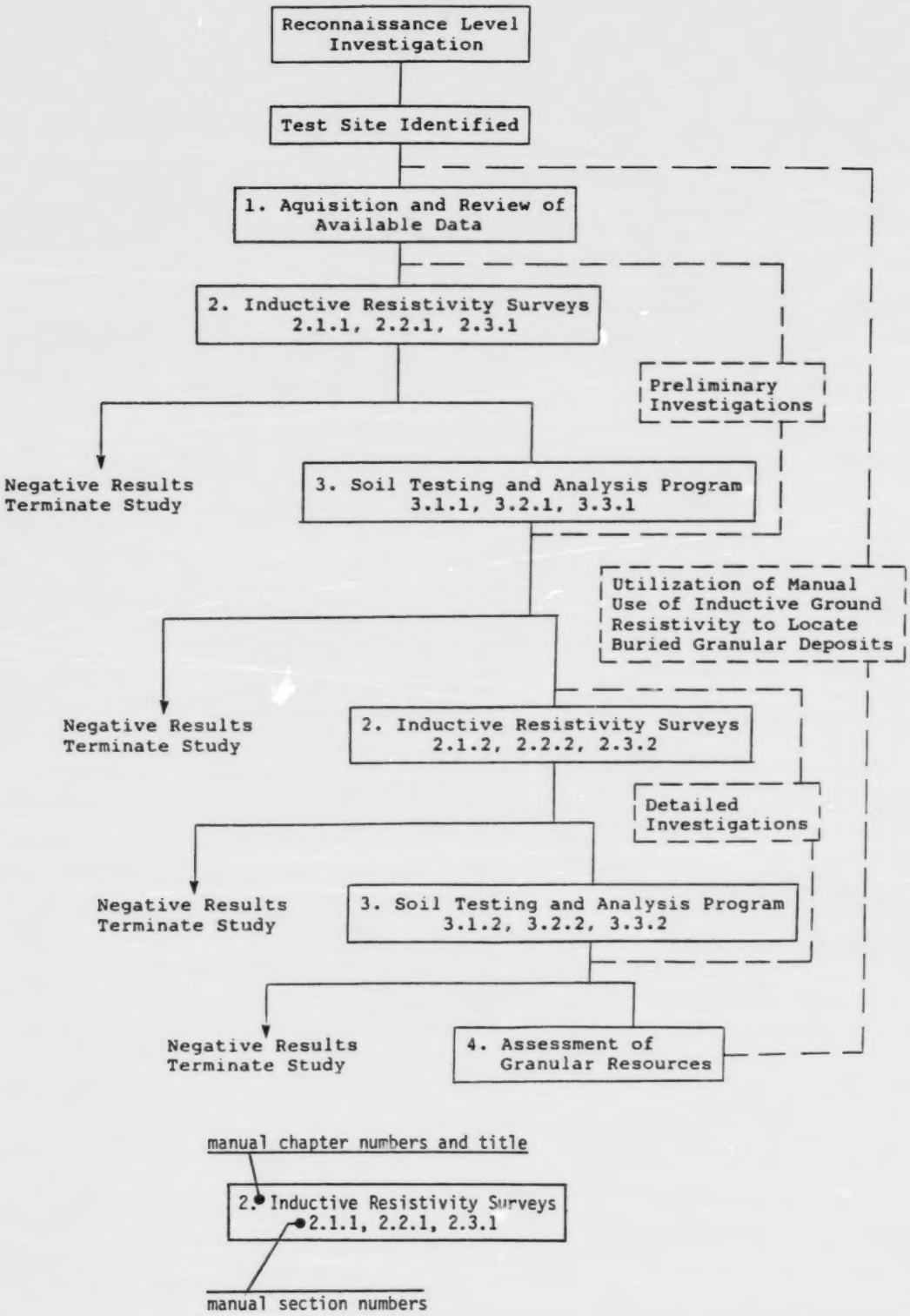

Reconnaissance Level Investigation
Test Site Identified
1. Aquisition and Review of Available Data
2. Inductive Resistivity Surveys 2.1.1, 2.2.1, 2.3.1
Preliminary Investigations
Negative Results Terminate Study
3. Soil Testing and Analysis Program 3.1.1, 3.2.1, 3.3.1
Utilization of Manual Use of Inductive Ground Resistivity to Locate Buried Granular Deposits
Negative Results Terminate Study
2. Inductive Resistivity Surveys 2.1.2, 2.2.2, 2.3.2
Detailed Investigations
Negative Results Terminate Study
3. Soil Testing and Analysis Program 3.1.2, 3.2.2, 3.3.2
Negative Results Terminate Study
4. Assessment of Granular Resources
manual chapter numbers and title
2. Inductive Resistivity Surveys 2.1.1, 2.2.1, 2.3.1
manual section numbers

Figure 1. Flow Chart Showing Decision Process for Buried Granular Material Investigations

APPENDIX A

Technical Note TN-5:

Electrical Conductivity of Soils and Rocks

(Source: McNeill,J.D., 1980. Geonics Ltd.)

I. INTRODUCTION

It was near the beginning of this century that Conrad Schlumberger first employed the technique of mapping sub-surface geology by injecting electrical currents into the ground and mapping the resulting potential field distribution. Since that time measurement of terrain resistivity has been applied to a variety of geological problems. A partial list of applications includes the determination of rock lithology and bedrock depth; the location and mapping of aggregate and clay deposits; mapping groundwater extent and salinity; detecting pollution plumes in groundwater; mapping areas of high ice content in permafrost regions; locating geothermal areas; mapping archaeological sites, etc.

In many instances resistivity mapping provides definite geological information; however there are also cases where the results are uninterpretable since the "geological noise" is too high. A limitation of resistivity surveying is that the actual value of terrain resistivity itself is seldom diagnostic. As a result of this ambiguity we generally examine the variations of resistivity, either laterally or with depth, to outline the geological features of interest. But a problem arises in that conventional surveys are time-consuming to carry out and the area actually surveyed is often smaller than one might wish in order to fully ascertain the background against which the anomalous feature is to be defined. Furthermore, although conventional resistivity techniques sense to a characteristic depth (determined by the interelectrode spacing) resistivity inhomogeneities much smaller than that depth can, if they are located near the potential electrodes, yield large errors in the measurement and thus a noisy survey profile.

For these reasons application of resistivity surveys to engineering problems is not as common as it might be, particularly in North America. Such surveys have achieved success in Europe and are used more routinely.

It was an awareness both of the potential of resistivity measurements for solving geological problems and equally of some of the drawbacks of conventional resistivity mapping which lead Geonics Limited to develop two new lines of instrumentation employing electromagnetic techniques to measure terrain conductivity. In the first of these a sinusoidally varying magnetic field electromagnetically induces currents in the ground in such a manner that their amplitude is linearly proportional to the terrain conductivity (reciprocal of resistivity). The magnitude of these currents is determined by measuring the magnetic field which they in turn generate. Through the use of electromagnetic techniques, ground contact is avoided and with these patented instruments it is possible to map terrain conductivity virtually as fast as the operator(s) can walk; furthermore the sample volume is averaged in such a manner as to yield excellent resolution in conductivity. Two instruments have been developed by Geonics to cover the range of depths generally useful for engineering geophysics: (i) the EM31, one-man portable, has an effective penetration depth of 6 meters and (ii) the EM34-3, two-man portable, has stepwise selectable depths from 7.5 meters to 60 meters.

In the second approach the current flowing in a loop situated on the ground is abruptly terminated, inducing eddy currents in the ground which diffuse away from the transmitter loop in a manner controlled by the ground conductivity. In this case the dispersal of the currents is determined by measuring the transient decay of their magnetic field. Based on this principle, the Geonics EM37 can be used to determine the electrical properties of the earth to depths of several hundred meters.

These devices are assisting in the solution of many geological problems. With the renewed interest in resistivity it has become apparent that there is a requirement for a short note which discusses, from the point of view of survey interpretation, the various factors that influence terrain resistivity. For example, typical questions raised include (1) When are gravels more resistive than finer material? (2) What is the influence of the depth to water table? (3) It rained heavily last week; will this affect the measurements? (4) What are typical resistivities for the following soil types?, etc., etc.

By describing the various factors that control the electrical conductivity/resistivity of soils and rocks under typical in-situ conditions this note will attempt to provide the technical background against which these questions can be answered and to thus give the operator greater confidence in his survey interpretation. The emphasis throughout this technical note is on those factors that influence the near-surface ground resistivity, particularly of soils.

The various topics are dealt with in the following sequence.

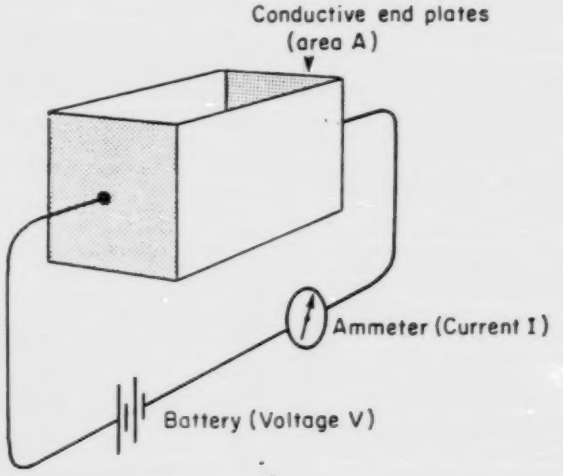
Section II: definition of conductivity & resistivity
Section III: description of relevant physical properties of soils and rocks
Section IV: relation of physical properties to the electrical conductivity
Section V: discussion of conventional resistivity measurements of soils in different climatic zones.

As mentioned above, this technical note is directed towards the user. Many readers will be familiar with the physical properties of soils and we ask their indulgence. None of the material on the electrical properties of soils is original; some has been taken verbatim from the references. However the compilation has been derived from many sources and we hope that it will prove useful.

II. RESISTIVITY/CONDUCTIVITY

Basically the electrical resistivity/conductivity of a substance is a measure of the difficulty/ease with which an electrical current can be made to flow through it. Suppose that we construct a tank with insulating sides and two conductive end plates as shown in Figure 1. The end plates are connected to a battery through an ammeter with which we measure the current flow through the sample. If the tank is empty there is of course no path by which the current can flow from one end plate to the other and the ammeter reads zero.

Suppose we fill the tank with a mixture of clean gravel and tap water. The ammeter will read a finite current and, depending on



RESISTIVITY (ρ)

$\rho = \frac{R A}{L}$ ohm-metres

where $R = \frac{V}{I}$ ohms

CONDUCTIVITY (σ)

$\sigma = \frac{G L}{A}$ mhos/meter

where $G = \frac{I}{V}$ mhos

FIGURE 1. Resistivity/conductivity tank.

various parameters to be discussed in Section IV, might indicate a current flow of a few thousandths of an ampere i.e. a few milliamperes, for a voltage of one volt. If the ammeter reads two milliamperes the electrical resistance of the material in the tank, given by the ratio of the voltage divided by the current, is 500 ohms.

If we now fill a number of different rectangular tanks, of different dimensions, with the same mixture we would find that the electrical resistance is proportional to the length of the tank and inversely proportional to the area of the conductive plate electrodes. The constant of proportionality, a property of the mixture only, independent of the tank dimensions, is defined as the electrical resistivity. In the MKS system it has the units of ohm-meters and is the electrical resistance measured on a cubic sample whose dimensions are all one meter. In the CGS system of units the resistivity is defined as the resistance across two opposite faces of a cubic sample one centimeter on each side and the units are ohm-centimeters. From the defining relation we see that, given the resistivity in ohm-centimeters, we must divide by 100 in order to get the resistivity in ohm-meters.

Suppose that we empty our tank (now assumed to be one meter on a side) and fill it with a mixture of clay saturated with water. We might find that the ammeter read a few tenths of an ampere, perhaps as much as half an ampere. The resistance would then be two ohms, the resistivity two ohm-meters. The range of resistivities displayed by unconsolidated materials at temperate ambient temperatures usually lies between one ohm-meter and one thousand ohm-meters; the resistivity of rocks can vary from a few tens of ohm-meters to as high as 100,000 ohm-meters, discussed in further detail in Section IV.

The reciprocal of the electrical resistivity of our sample is defined as the electrical conductivity. In the MKS system the unit of conductivity is the mho per meter and a resistivity of one ohm-meter exhibits a conductivity of one mho per meter, 100 ohm-meters is equivalent to a conductivity of 0.01 mhos per meter, etc. The electromagnetic instruments actually measure terrain *conductivity* rather than *resistivity* and for this reason much of the remainder of this technical note will be concerned with the conductivity of various terrain materials rather than the resistivity.

It was stated above that a resistivity of 100 ohm-meters corresponds to a conductivity of 0.01 mhos per meter. To avoid the inconvenience of having zeros immediately following the decimal point all conductivities will be expressed in millimhos per meter: a conductivity of .01 mhos per meter corresponds to 10 millimhos per meter, etc. This has the advantage that the range of resistivities from 1 to 1,000 ohm-meters is covered by the range of conductivities from 1,000 to 1 millimhos per meter and such numbers are easily handled. Table 1 lists the conversion from resistivity and conductivity in various units to conductivity in millimhos per meter.

In the experiments described above a direct current was employed. Had we used an alternating current and varied the frequency we might have discovered that the electrical properties of the sample varied with frequency. In reality soils and rocks are complex substances in which there are many (some poorly understood) mechanisms which govern the mode of current flow through the sample [1–5].

TABLE 1. Resistivity/conductivity unit conversion factors

mhos/meter × 1000	→ millimhos/meter
$\frac{1000}{\text{ohm-meters}}$	→ millimhos/meter
$\frac{100{,}000}{\text{ohm-centimeters}}$	→ millimhos/meter
$\frac{\text{cgs electrostatic units}}{9 \times 10^8}$	→ millimhos/meter

Note: 1 Siemen (S) = 1 mho

Fortunately, for materials with conductivity of the order of one to 1,000 millimhos per meter the electrical properties which control the current flow are relatively independent of frequency and the DC or low frequency conductivity measured with conventional resistivity equipment will be essentially the same as that measured using low frequency electromagnetic techniques.

Finally it should be noted that measurement of the electrical conductivity or resistivity of geological samples is, in reality, a very difficult procedure requiring much more complex equipment than the simple tank referred to above.

III. FACTORS AFFECTING TERRAIN CONDUCTIVITY

Most soil and rock minerals are electrical insulators of very high resistivity. However on rare occasions conductive minerals such as magnetite, specular hematite, carbon, graphite, pyrite and pyrrhotite occur in sufficient quantities in rocks to greatly increase their overall conductivity. This note assumes that such minerals are absent.

In general the conductivity is electrolytic and takes place through the moisture-filled pores and passages which are contained within the insulating matrix. The conductivity is therefore determined for both rocks and soils by

(1) porosity: shape and size of pores, number, size and shape of interconnecting passages
(2) the extent to which pores are filled by water i.e. the moisture content
(3) concentration of dissolved electrolytes in the contained moisture
(4) temperature and phase state of the porewater
(5) amount and composition of colloids

Since the constituents, structure, and included moisture of soil or rock are of great importance in determining the conductivity, this section will discuss the various physical and chemical properties in sufficient detail to illustrate how they affect the material conductivity.

III. 1. Soil Constituents

Soils consist basically of four components namely (i) mineral material (ii) organic material (iii) water and (iv) gases.

Figure 2 shows schematically the relative proportion of these components in an unsaturated loam soil (to be defined later). The illustration refers to a temperate zone soil; for humid region soils about 45% of the solid space may be occupied by clay minerals and 5% by organic matter.

The mineral fraction of a soil can be extremely variable, however some generalizations can be made based on grain size [6]:

sand size range – mostly quartz, small amounts of feldspar and mica present, all grains coated to some extent with iron and aluminum oxide (the rusty reddish-brown colour observed is due to the iron).

silt size range – quartz still dominant, less feldspar and mica than in the sand fraction, more iron and aluminum

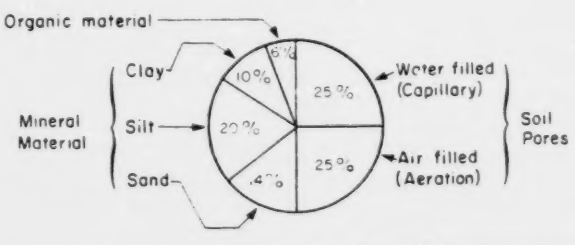


FIGURE 2. The volumetric composition of a loam soil when excess water has been removed. On a weight basis the percentage composition of the dry soil would be: organic matter 4%, clay 22%, silt 44% and sand 30% (after L.R. Webber [6]).

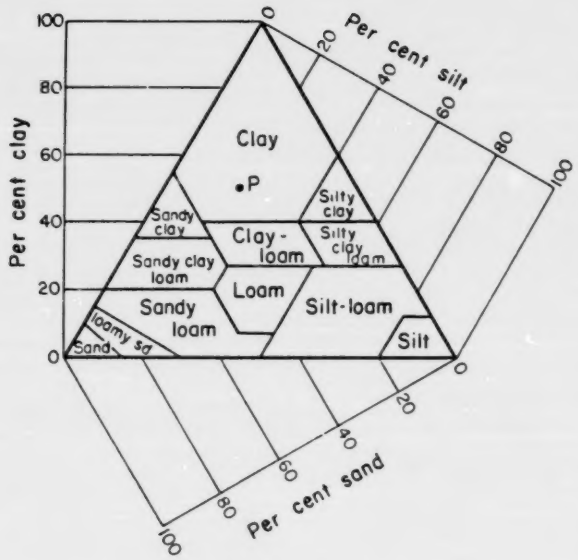


FIGURE 3. U.S. Department of Agriculture textural classification triangle with axes added. The point P represents a clay (soil) containing 50 per cent clay, 20 per cent silt, and 30 per cent sand (after D. Kirkham [7]).

oxides in the form of coatings due to the greater particle surface area on which the coatings may reside.

clay size range – finely divided quartz, feldspar, mica, iron and aluminum oxides, all of which appear in the coarser part of the clay fraction (0.002 millimeters – 0.001 millimeters in diameter); the finer part (less than 0.001 millimeters) is colloidal and consists mainly of layer silicates with smaller amounts of iron and aluminum oxides.

As indicated above soils are classified on the basis of texture or grain size independently of the mineralogical content of each particle size component. Sand is defined as particles with diameters between 0.05 millimeters and 2 millimeters, silt has diameters between 0.002 millimeters and 0.05 millimeters and clay has diameters less than 0.002 millimeters. Figure 3 shows the classification triangle for various types of soil and is useful as it allows an estimate of the clay content which often consists essentially of clay minerals which affect the soil conductivity.

The minerals in the sand and silt fractions of the soil are electrically neutral and are generally excellent insulators. Completely dry clay is also an insulator but the introduction of moisture changes the situation radically. Clay consists of microscopically fine particles

TABLE 2. Exchange capacity of common clays (after Keller and Frischknecht [5])

Clay	Exchange Capacity
Kaolinite	3 to 15 m-equiv/100 g
Halloysite . $2H_2O$	5 to 10
Halloysite . $4H_2O$	40 to 50
Montmorillonite	80 to 150
Illite	10 to 40
Vermiculite	100 to 150
Chlorite	10 to 40
Attapulgite	20 to 30

TABLE 3. The cation exchange capacity (CEC) and colloid content of five soils of different textures (after L. R. Webber [6]).

Soil Texture	Organic Matter %	Clay %	CEC* me 100 g
Sand	1.7	7	6.3
Sandy loam	3.2	13.2	13.7
Loam	4.9	16.8	20.2
Silt loam	5.4	18.4	24.0
Clay loam	5.5	31.2	27.2

*The cation exchange capacity of a soil is expressed in terms of milliequivalents per 100 grams of soil (meq/100 g). A milliequivalent is defined as 1.0 milligram of hydrogen or the amount of any other element that will combine with or displace it. The milliequivalent weight of any element may be found as follows:

$$\frac{\text{atomic weight of element}}{\text{valence of element} \times 1000} = \text{milliequivalent weight}$$

exhibiting a sheet-like structure, for which reason clays are often called "layer silicates". Composed of stable secondary minerals that have formed as a result of weathering of primary minerals such as feldspar, mica, etc. the particles are so fine-grained that they are described as micro-crystals.

Their crystalline structure is such that, as a result of crystal imperfections, the surface appears to be negatively charged [5]. During the formation of the clay through weathering, positive charges (cations) are adsorbed to the surface. These cations (typically Ca, Mg, H, K, Na, NH_3) are loosely held to the surface and can subsequently be exchanged for other cations or essentially go into solution should the clay be mixed with water. For this reason they are called exchangeable ions and the cation exchange capacity (CEC) of the soil is a measure of the number of cations that are required to neutralize the clay particle as a whole i.e. the weight of ions in milliequivalents adsorbed per 100 grams of clay.

The exchange capacities of some common clays are given in Table 2 and of some different soil textures in Table 3. It is seen from Table 3 that the cation exchange capacity increases with clay content and from Table 2 that this will depend on the type of clay.

Clay minerals are not the only materials which have cation exchange capacity; indeed any fine-grained mineral including quartz displays this property. The special significance of clay in this respect is that, because of the extremely small particle size, the surface area per unit volume of clay is very large and a great many ions are adsorbed. It will be seen in the next section that these adsorbed ions can contribute appreciably to the soil conductivity which thus becomes a function of the clay content.

The organic matter includes the remains of plant and animal life in the soil. The end products of decay accumulate as a blackish, finely-divided colloidal substance known as humus [6] which has large surface area per unit volume, takes up large amounts of water and can develop a negative electrical charge of varying intensity. Little is known of the effects of such colloidal characteristics on the electrical conductivity of humus but they may be significant.

The important influence of soil moisture on the electrical conductivity of soils is discussed at length in a later section.

The direct effect of soil gases on conductivity is negligible, however the indirect effect of CO_2 is important and is also described in a later section.

III. 2. Formation of Soils [8] and Soil Profiles [9]

Soils are the result of mechanical, chemical, and biological weathering processes acting on surficial materials in such a way as to grossly alter their physical and chemical properties. In the process of decomposition of parent materials new and stable substances such as clay minerals and humic materials are formed.

As an example of the weathering process consider the chemical

weathering of orthoclase feldspar (an important constituent of granites and other intrusive rocks) to kaolinite, a clay. Atmospheric carbon dioxide is slightly soluble in water so as to form carbonic acid.

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \rightleftharpoons \underset{\text{Carbonic acid}}{H_2CO_3} \qquad (1)$$

A small amount of the carbonic acid dissociates so as to produce a hydrogen ion and a bicarbonate ion

$$H_2CO_3 \rightleftharpoons \underset{\text{Hydrogen ion}}{H^+} + \underset{\text{Bicarbonate ion}}{HCO_3^-} \qquad (2)$$

The bicarbonate ion and water combine with the feldspar to form kaolinite, dissolved silica, free potassium ions and free bicarbonate ions

$$\underset{\text{Orthoclase feldspar}}{2K\,Al\,Si_3O_8} + 2H^+ + 2HCO_3^- + H_2O \longrightarrow \qquad (3)$$

$$\underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_4} + 4\,\underset{\text{Silica}}{SiO_2} + \underset{\text{Potassium ion}}{2K^+} + \underset{\text{Bicarbonate ion}}{2HCO_3^-}$$

The formula for kaolinite can also be written in the following manner

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$$

to show that it consists of alumina, silica, and water.

These equations illustrate three important points: (i) The potassium and silica produced by dissolving the feldspar appear as dissolved material. Note that the potassium, converted to a potassium ion, goes into solution and may or may not be present depending on the drainage. (ii) Water is used up in the reaction; it is absorbed into the kaolinite structure. (iii) Hydrogen ions are used up in the reaction and the solution becomes more basic (i.e. less acidic) as the reaction proceeds. All of the reactions described herein affect the electrical properties of the soil by varying either the clay content or the ionic type and concentration in the soil water.

Now let us examine how various factors control this weathering process. The production of soil is a positive feedback process in that once a thin veneer of soil forms, the parent material weathers more rapidly, and more soil is formed. Suppose for example that we have a thin layer of soil on granite. This layer retains moisture which supplies both water that converts carbon dioxide to carbonic acid and water that is hydrated to form kaolinite. Other acids present in the soil contribute additional supplies of hydrogen ion to convert more feldspar to kaolinite as the equations indicate. Plant roots and the process of bacterial decay produce quantities of carbon dioxide to yield more carbonic acid (the amount of carbon dioxide in soil can be as much as ten times greater than that of rainwater, which makes soil water a particularly efficient dissolver of feldspars).

The speed of weathering is a function of climatic type since the rate at which chemical reactions proceed increases with temperature and, more importantly, biological process also proceed faster with higher temperature. Furthermore, since water is needed for the weathering reactions and vegetation grows more lushly in humid climates weathering is most intense in tropical climates which are wet and warm. The surface water resulting from rainfall percolates downwards through the soil, which is more or less permeable, and as it passes reacts chemically with minerals within the soil. The higher the rainfall the more water is available and the more the minerals will react with the undersaturated water. The longer the time the water percolates through, the more time it has to react chemically and again the higher the temperature, the faster the reaction rates.

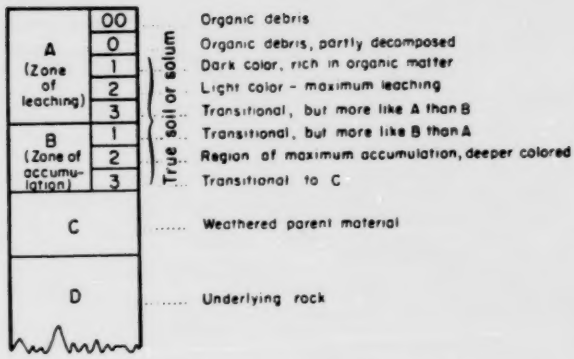


FIGURE 4. Normal or zonal soil profile (after G.B. Maxey [9]).

As a result of these factors tropical soils tend to be thick. Well drained soils tend to be devoid of most unstable minerals. Arid soils contain a variety of minerals. The clay minerals which form are a function of temperature and humidity and there is a tendency for different clays to form in the various climatic belts [10].

As long as there is rainfall and the temperatures are not too low there is a tendency for soils to form a layered structure. In general three different regions or horizons are recognized as we move down through the soil profile, usually designated by the letters A, B, and C. These horizons can vary in thickness from a centimeter to several meters or tens of meters and differ in colour, texture, structure, and other properties.

The chief characteristics of a profile are illustrated in Figure 4. The A horizon, closest to the surface, is the most intensely weathered and has the soluble minerals leached out and most other minerals altered. This layer usually contains much humus, which contributes to its dark colour. Structurally it is friable, granular, or platey. When either friable or granular this horizon is permeable, much more so than the underlying B horizon which is generally a zone of clay accumulation, some of which was formed in-situ and some of which was transported downwards from the A zone by the soil water. The B horizon generally displays a vertical structure in widely or closely spaced joints and it is this horizon that exerts the greatest influence on water movement vertically downwards. When the clay is dry these joints allow rapid downwards movement but when the clay is wet it expands and can close the joints to make the layer impermeable, which may in turn cause the A horizon to become saturated for appreciable periods of time. The C horizon consists of less-weathered parent material and is usually relatively permeable [9].

This layering, with its relatively clay-free A horizon and clay-rich B horizon, greatly influences the vertical profile of electrical conductivity which will be seen to be a function of both clay and water content.

III. 3. Soil Moisture

It was noted at the beginning of this section that the electrical conductivity of soils and rocks was primarily electrolytic and took place through the moisture filled pores and passages which lie within the matrix of insulating minerals. For this reason a knowledge of the way in which soil moisture is distributed in typical terrain is important in understanding terrain conductivity.

When rainwater or irrigation falls on the surface of the soil a fraction runs off directly as surface runoff and the remainder percolates directly into the soil. A fraction of this moisture is retained by the soil, the remainder moves vertically downwards under the force

of gravity until it reaches the water table. In a soil moisture profile it is generally possible to distinguish four stages of moisture occurrence depending on the relative continuity of the moisture films across the soil grains [11] as shown in Figure 5. In the uppermost region we have the pendular state in which the pore space is largely filled with water vapour. The actual liquid water exists only in very small isolated rings around the grain contacts and a continuous path does not exist between the various moisture occurrences. At greater depth we have the funicular stage in which the pendular rings have coalesced to the point where the liquid films have just become continuous throughout the pore space and entirely enclose or encapsulate the vapour phase. Across the sample the moisture path is now continuous. Again further down, in the capillary stage, all pore spaces are occupied by liquid but the liquid pressure within the pores is less than the total pressure caused by gravity since capillary action within the fine pore spaces has caused the moisture to ascend into these pore spaces. Capillary rise, determined effectively by pore size and type, seldom exceeds several meters. Finally we arrive at the phreatic surface (water table) at which the atmospheric pressure is in equilibrium with the hydrostatic pressure. All pores within the phreatic surface are completely filled with liquid under hydrostatic pressure and this is the region of groundwater, also known as the zone of saturation. The three regions above the phreatic surface are collectively referred to as soil moisture, suspended water, vadose water, or zone of aeration.

Figure 5 also illustrates typically the fraction of pore space filled by liquid in the different zones.

A term that is often used in discussing the moisture content of soils is field capacity. Suppose that the water table is very deep below a surface soil of homogenous nature. After a heavy rainfall or irrigation the moisture content reaches a quasi-equilibrium condition in one to three days. As the water percolates down through the soil on its way to the water table capillary forces will retain a certain fraction of the moisture in the small pore spaces. This is the field capacity and it is the moisture content of the soil after the gravitational water has been removed by deep seepage.

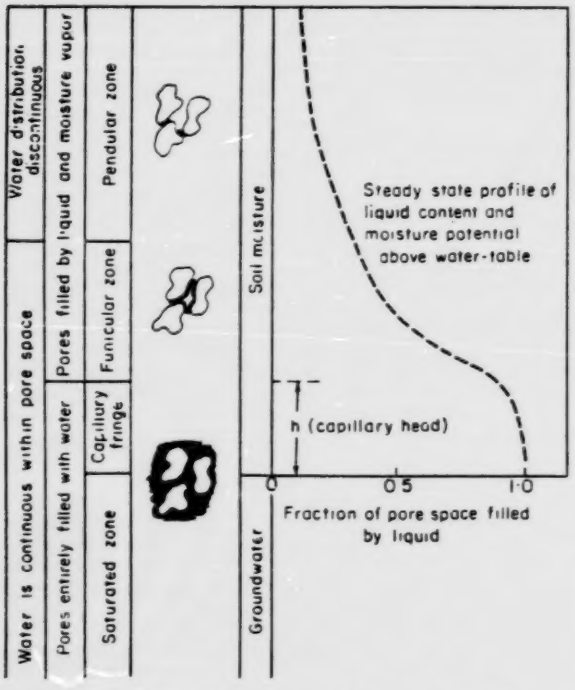


FIGURE 5. Liquid occurrence in soils (after P. Meyboom [11]).

TABLE 4. Permeability of soils (after D. K. Todd [12])

SOIL CLASS						
FLOW CHARACTERISTICS	Good aquifers			Poor aquifers		Impervious
PERMEABILITY (gpd/sq ft/ft)	10^{3}	10^{2}	10^{1}	1	10^{-1}	10^{-2}

Note that in the event that we have a layered situation in which a soil with very fine pores overlies more granular material, both being far removed from the water table, moisture content of the upper layer will be many times that of the lower which, as will be seen later, affects the electrical conductivity.

Groundwater is free to move laterally with velocities ranging from a meter or more per day to less than a meter per year, depending on the hydraulic pressure differential and the permeability of the material. Table 4 illustrates the permeability of various materials in gallons per day per square foot of cross-section per foot of hydraulic head per lateral foot of distance. It is seen from the Table that for soil materials a factor of 10^{10} separates permeable from impermeable materials. The saturated hydraulic conductivity decreases with clay content, increasing compaction, and decreasing radius of the soil pores.

The laws of hydraulic movement of water produce a water table which in general is not horizontal and in fact is often a subdued version of the local topography, all other factors being equal. Two examples are shown in Figure 6; for the humid zone the moisture moves from topographic high regions down to the draining streams whereas in an arid zone the moisture moves downwards away from the streams.

The wide ranges of permeability greatly influence the final profile of the water table or phreatic zone sometimes leading, for example, to the occurrence of a perched water table as shown in Figure 7. Again such layering will be seen subsequently to influence the electrical properties.

It will be shown in Section IV that the electrical conductivity of soils and rocks depends on the porosity and on the degree to which the pores are filled with moisture. Figure 2 showed the volumetric composition of a loam soil from which the excess water has been removed i.e. the soil is undersaturated. We see that in this temperate zone example approximately 50% of the soil is occupied by either gas or capillary water. This division into about 50% solids is fairly typical of most soils.

If all of the moisture in a soil sample is removed by drying, the ratio of the empty volume to the total volume of the soil matrix is known as the soil porosity, a parameter that is relevant to the soil conductivity. Table 5 illustrates the porosity for a variety of typical terrain materials.

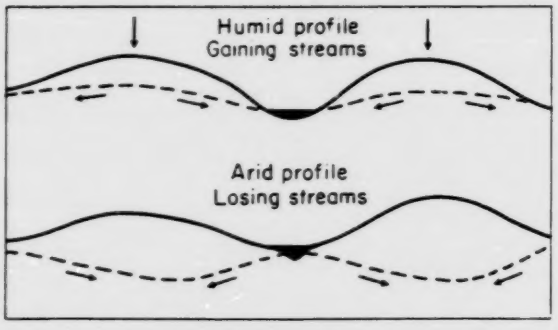


FIGURE 6. Profiles of water tables in arid and humid zones (after G. B. Maxey [9]).

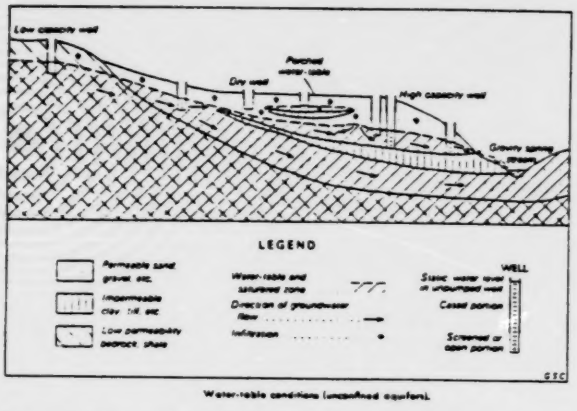


FIGURE 7. Water-table conditions – unconfined aquifers (after I.C. Brown [13]).

TABLE 5. Representative porosity ranges for sedimentary materials (after D. K. Todd [12])

Material	Porosity, %
Soils	50–60
Clay	45–55
Silt	40–50
Medium to coarse mixed sand	35–40
Uniform sand	30–40
Fine to medium mixed sand	30–35
Gravel	30–40
Gravel and sand	20–35
Sandstone	10–20
Shale	1–10
Limestone	1–10

Table 6 gives further data on porosity and also indicates the value of the ratio ρ_s (mixture resistivity) divided by ρ_1 (electrolyte resistivity) about which more will be said later in Sections IV and V.

It is obvious that the degree of compaction of a soil will affect the magnitude of the soil porosity.

IV. ELECTRICAL CONDUCTIVITY OF SOILS AND ROCKS

In Section III it was noted that the conductivity of soils and rocks was principally electrolytic. This section will discuss the parameters that determine the conductivity of electrolytes and the effects that arise when electrolytes are present in both clay-free and clay-rich soils and rocks.

IV. 1. Properties of Electrolytes

As an introduction suppose we empty our hypothetical tank of Section II and refill it with distilled water. The measured conductivity is very low. If however a small amount of table salt (NaCl) is dissolved in the distilled water the conductivity increases substantially.

TABLE 6. Porosity of soils and rocks (after C. A. Helland [14])

Rock or Formation	Porosity	Ratio $\frac{\rho_s}{\rho_1}$
Igneous and metamorphic rocks	½– 2	100
Dense limestones and sandstones	3– 4	50 –100
Clays and sands in general	8–15	20 – 40
Porous clays, sands, sandstone, cellular limestones, and dolomites	15–40	3 – 20
Marl, loess, clay, and sandy soil	40–75	1.5– 4
Peat, diatomaceous earth	80–90	1.0– 1.5

TABLE 7. Mobility of common ions at 25°C (after Keller and Frischknecht [5])

ion	Mobility (m^2/sec V)
H^+	36.2×10^{-8}
OH^-	20.5×10^{-8}
SO_4^-	8.3×10^{-8}
Na^+	5.2×10^{-8}
Cl^-	7.9×10^{-8}
K^+	7.6×10^{-8}
NO_3^-	7.4×10^{-8}
Li^+	4.0×10^{-8}
HCO_3^-	4.6×10^{-8}

The conductivity of an electrolyte is proportional both to the total number of charge carriers (ions) in the solution and their velocity. In distilled water there are few ions and the conductivity is low. The dissolved sodium chloride molecules dissociate to form both positively charged sodium ions and negatively charged chloride ions which greatly increase the conductivity.

When a voltage is applied between the two end plates an electric field is established in the tank; the positively charged ions are attracted towards the negative plate, the negatively charged ions to the positive plate. The velocity of the ions is effectively controlled by the viscosity of the fluid. This velocity is slightly different for different ions since it depends upon their effective diameter, as illustrated in Table 7, where it can be seen that chloride ions move slightly more rapidly than the sodium ions.

In a sodium chloride solution the amount of current that flows, and therefore the electrical conductivity, is proportional to the sum of the number of sodium ions multiplied by their mobility (velocity per unit electric field) and the number of chloride ions multiplied by their mobility.

The further addition of different salts to our tank would increase the electrical conductivity independently of the presence of the sodium and chlorine ions as long as the concentrations remain reasonably dilute. The following equation is often used to calculate the approximate electrical conductivity in mhos per meter of a dilute solution of various salts at normal ambient temperatures:

$$\sigma = 96500[C_1M_1 + C_2M_2 + \ldots] = 96500 \sum C_iM_i \quad (4)$$

where C_i = no. of gram equivalent weights of i^{th} ion per 10^6 cm^3 of water

M_i = mobility of i^{th} ion in meters per second per volt per meter.

For example, suppose that one gram of salt is dissolved in our tank which holds 10^6 cm^3 of water. The atomic weight of sodium is 23, of chlorine is 35, so the atomic weight of sodium chloride is 23 + 35 = 58. Since we have introduced one gram of sodium chloride we have introduced

$$\frac{23}{58} \text{ grams of sodium and } \frac{35}{58} \text{ grams of chlorine.}$$

The gram equivalent weight of an ion is the atomic or molecular weight of the ion divided by its valence. In the case of both sodium and chlorine the valence is one so the gram equivalent weight of sodium is 23 grams, of chlorine 35 grams.

Then the number of gram equivalent weights of sodium per 10^6 cm^3 of water is given by

$$C_{Na} = \frac{\text{weight of Na per } 10^6 \text{ cm}^3 \text{ } H_2O}{\text{gram equivalent weight}} = \frac{23/58}{23} = \frac{1}{58}$$

and that for chlorine is given by

$$C_{Cl} = \frac{\text{weight of Cl per } 10^6 \text{ cm}^3 \text{ } H_2O}{\text{gram equivalent weight}} = \frac{35/58}{35} = \frac{1}{58}$$

Using the data from Table 7 for the mobilities at 25° C we find that the conductivity for one gram of sodium chloride in 10^6 cm^3 of water is given by

$$\sigma = 96500\left[\frac{1}{58} \times 5.2 \times 10^8 + \frac{1}{58} \times 7.9 \times 10^8\right]$$

$$= 0.00022 \text{ mho/m.} \quad (5)$$

The addition of only one part per million of sodium chloride by weight has produced the appreciable conductivity of 0.22 millimhos per meter.

The concentration of dissolved salts in natural groundwaters is substantially higher than one part per million, as a result of which their conductivity is much greater than 0.22 millimhos per meter. For example Table 8 illustrates the contribution of various ions to the measured conductivity of three of the Great Lakes. Lakes Erie and Huron which both occur in regions of Paleozoic carbonate rocks contain more dissolved salts than Lake Superior which is situated largely in Precambrian crystalline rocks, and this is reflected in the higher conductivities of the first two lakes. The bottom line of the table gives the measured conductivity: agreement with the calculated values using the above equations is good.

The following data from Heiland [14] illustrates typical values for the conductivity of various natural waters.

1. Meteoric waters, derived from precipitation: 1 to 30 millimhos per meter.
2. Surface waters (lakes, rivers) vary from 0.3 millimhos per meter for very pure water to as large as 10,000 millimhos per meter for salt lakes. Surface waters in districts of igneous rocks are estimated to range from 2 to 30 millimhos per meter; surface waters in areas of sedimentary rocks vary from 10 to 100 millimhos per meter (compare the Great Lakes above).
3. Soil waters (discharged into the atmosphere by evaporation) may be as large as 10,000 millimhos per meter but their average is around 10 millimhos per meter.
4. Normal groundwater in areas of igneous rock ranges from 6 to 30 millimhos per meter and in areas of sedimentary rocks to as large as 1,000 millimhos per meter.
5. Mine waters (copper, zinc, etc., sulfates) are of high conductivity, generally not less than 3,000 millimhos per meter.

TABLE 8. Conductivity of Great Lakes with contribution of the various ions (after L. H. Doherty [15])

Ion	Lake Erie	Lake Huron	Lake Superior
HCO_3	5.8	4.1	2.6
Ca	10.1	7.3	3.8
Mg	3.6	3.2	2.4
Na	1.8	0.6	0.2
Ci	3.9	1.2	0.2
SO_4	3.4	1.8	0.3
Calculated Conductivity (mmhos/m)	28.6	18.2	9.5
Measured Conductivity (mmhos/m)	26.7	18.2	8.4

The temperature dependence of the electrical conductivity of the electrolyte is almost entirely due to the temperature dependence of the viscosity of the liquid, which in turn directly affects the ionic mobility. The variation of either quantity with temperature is approximately linear over normal ambient temperatures. The temperature coefficient for a sodium chloride solution is 0.022 which value applies approximately to most other ions so that the electrolyte conductivity for a temperature other than 25°C is given by

$$\sigma(T) = \sigma(25^\circ C)[1 + \beta(T - 25^\circ)]$$

where $\beta = 2.2 \times 10^{-2}$ per °C

T = temperature (°C) at which conductivity is to be calculated.

A change of conductivity of 2.2% per degree centigrade implies that a change in temperature of 40°C will cause the conductivity to nearly double. The effect of temperature is illustrated in Figure 8 which shows calculated conductivity of four of the Great Lakes as a function of season.

The change of conductivity with temperature and therefore with season is not negligible and this applies equally well to ground conductivity over the normal range of ambient temperatures.

IV. 2. Conductivity of Saturated Clean (Clay-Free) Mixtures

We have examined how the electrical conductivity of the electrolyte in our tank varies with the concentration of dissolved salts and with temperature. Let us now start to fill the tank with perfectly insulating spheres of uniform radius (for example uniform pebbles). Assume for the time being that we can maintain these spheres uniformly dispersed throughout the solution. Since the spheres are insulating, the electrical current will find it more difficult to cross the tank and the conductivity will be reduced. A relationship was derived by Maxwell for the conductivity σ_x of a mixture consisting of a medium with conductivity σ_1 in which spherical grains of conduc-

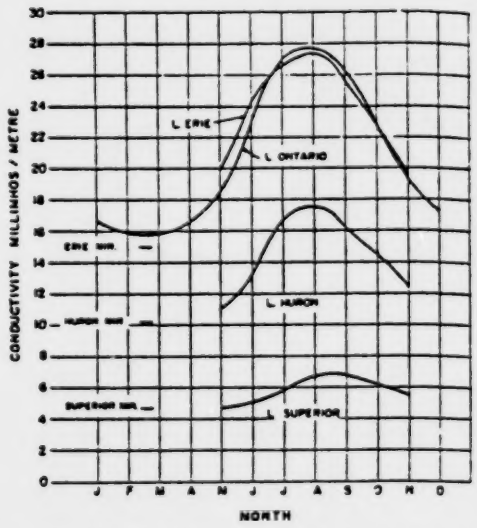


FIGURE 8. Seasonal variation of conductivity of Lakes Ontario, Erie, Huron and Superior (after L. H. Doherty [15]).

tivity σ_2 (here assumed to be zero) are imbedded in regular arrangement and in such a manner that their spacing is large compared with their radius [14]. Letting n be the porosity of the mixture (defined as the ratio of the volume of solution only, divided by the total volume of the solution including the spheres) Maxwell showed that the conductivity of the mixure was given by

$$\frac{\sigma_x}{\sigma_1} = \frac{2n}{3 - n} \tag{7}$$

In Section II it was shown that the conductance of a current path is directly proportional to the cross-sectional area and inversely proportional to the length. The addition of insulating spheres to the tank tends to reduce the cross-sectional area available for current flow and to increase the effective length of the current paths, reducing the overall conductivity.

This dilute mixture does not resemble a soil so we continue to add insulating spheres until the tank is full. The condition for Maxwell's derivation, that the inter-particle distance be large compared with the particle radius, is invalid and the above equation can no longer be expected to apply. It turns out however that an almost equally simple empirical relationship called Archie's Law [5] is applicable to clean (i.e. clay-free) saturated mixtures. This equation is

$$\frac{\sigma_x}{\sigma_1} = n^m \tag{8}$$

where n is the fractional porosity defined above and m is a constant. The reciprocal quantity ρ_x/ρ_1 is often called the formation factor (FF) of the rock or soil sample.

Originally derived from resistivity measurements on samples of consolidated porous rock, this equation also applies to a variety of unconsolidated materials. That such a simple law should give excellent results for a variety of both consolidated and unconsolidated materials with widely differing porosities is a surprise and indeed the underlying reasons for its success are not well understood [4]. It has been established [16] that in the case of marine sands the exponent m is dependent on the *shape* of the particles, increasing as they become less spherical (i.e. more platey) and that variations in the *size* of the particles and in the *dispersion* of sizes appear to have a very small effect.

Values of m are listed in Table 9 where it is seen that m varies from 1.2 for insulating spheres to 1.85 for very platey fragments of shell. Samples of natural sands have values in the range 1.4 to 1.6. The value of 1.85 for shell fragments is in good agreement with earlier measurements made on kaolinite particles and marine illite clays. This fact may or may not be significant for clays in normal soils depending on the extent to which ion exchange effects also contribute to the conductivity as discussed further on in this section.

Archie's Law for various exponents is plotted in Figure 9 along with Maxwell's Law. Over the range of porosities of most unconsolidated terrain materials (20% to 70% – see Tables 5 and 6) the different exponents do not greatly affect the mixture conductivity. Interestingly enough, Maxwell's Law gives excellent agreement with Archie's Law with exponent m = 1.3 over all ranges of porosity.

It would appear that for relatively clay-free substances located beneath the water table (so that the mixture is completely saturated) the primary matrix property measured through the electrical conductivity is the porosity of the matrix, essentially independent of the particle size or the particle size distribution. This explains why it is a relatively difficult matter using resistivity techniques to distinguish between sand and gravel. As long as the porosity is the same for both sand and gravel the resistivity or conductivity contrast may be quite small.

Another point is that if the porosity is assumed to vary from 20% to 70% the conductivity of the mixture varies by a factor of approximately 8, depending somewhat on which value of exponent is

TABLE 9. The effect of particle shape on the FF/n relation using artificial samples of decreasing sphericity. (after P. D. Jackson et al. [16])

Sample no.	Mean size ϕ*	Spread of sizes	Sphericity	Best fit Archie line FF = n^{-m} m ± 0.01
Spheres	0.38	0.17	1.0	1.20
Rounded sand	0.38	0.17	0.83	1.40
Shaley sand	0.50	0.34	0.78	1.52
Shell fragments	0.38	0.17	0.5	1.85

*$\phi = -\log_2$ (diameter in mm).

adopted. Even in clean mixtures we do not expect a large range of conductivities and experimentally this has been confirmed.

Figure 9 is useful for the following type of calculation: in many glacial deposits gravel appears as pebbles (of the order of a few centimeters in diameter) dispersed throughout a mixture of finer relatively clean sand. How does the presence of this gravel modify the mixture conductivity? To obtain an approximate answer let us assume that the sand itself has a porosity of 30%. Using Archie's Law with m = 1.6 the electrical conductivity of the sand/water mixture will be 15% of the conductivity of the water. Assuming a water conductivity of 20 millimhos per meter gives a conductivity for the mixture of 3 millimhos per meter, a not uncommon value. We use this value in conjunction with Figure 9 to determine the effect of introducing pebbles into the mixture. If for example the pebbles occupy 50% of the volume the conductivity of the mixture will fall to one-third or approximately 1 millimho per meter, also a value that commonly occurs in actual practice. As will be seen later the addition of a relatively small amount of clay can increase these numbers by virtue of increasing the conductivity of the pore water but the relative values may well be similar.

IV. 3. Conductivity of Unsaturated Clean Mixtures

For Archie's Law to apply the material must be fully saturated with fluid. If the mixture is partially saturated the conductivites will be decreased since gas or air bubbles act as insulating particles to further impede the current flow. In the funicular stage of soil moisture the pendular rings have coalesced so that the liquid films are continuous throughout the pore space but only a fraction of the available pore space is filled with water. This moisture varies with time and temperature as a result of drainage, evaporation, and loss of water to plant roots.

In the event that the soil is partially desaturated the following approximate expression applies [5]

$$\frac{\sigma_x}{\sigma_1} = s^n \tag{9}$$

where s is the fraction of total pore volume filled with electrolyte and n is a parameter experimentally determined to be approximately 2. This expression is equivalent to Archie's Law with m = 2 and indicates as seen from Figure 9 that if a small fraction of the total pore volume is filled with water the conductivity can be very low.

More recent work on soils has shown that the electrical conductivity varies as follows with moisture content when the soil is partially desaturated [17]

$$\sigma_x = \sigma_1\theta(a\theta + b) + \sigma_s \tag{10}$$

where θ is the volumetric water content (cm^3 of water per cm^3 of soil), a and b are constants which depend on the soil texture, and σ_s is a contribution from "surface conductivity" which will be discussed under Colloidal Conductivity. The values of the empirically determined constants a and b for a variety of soils are shown in

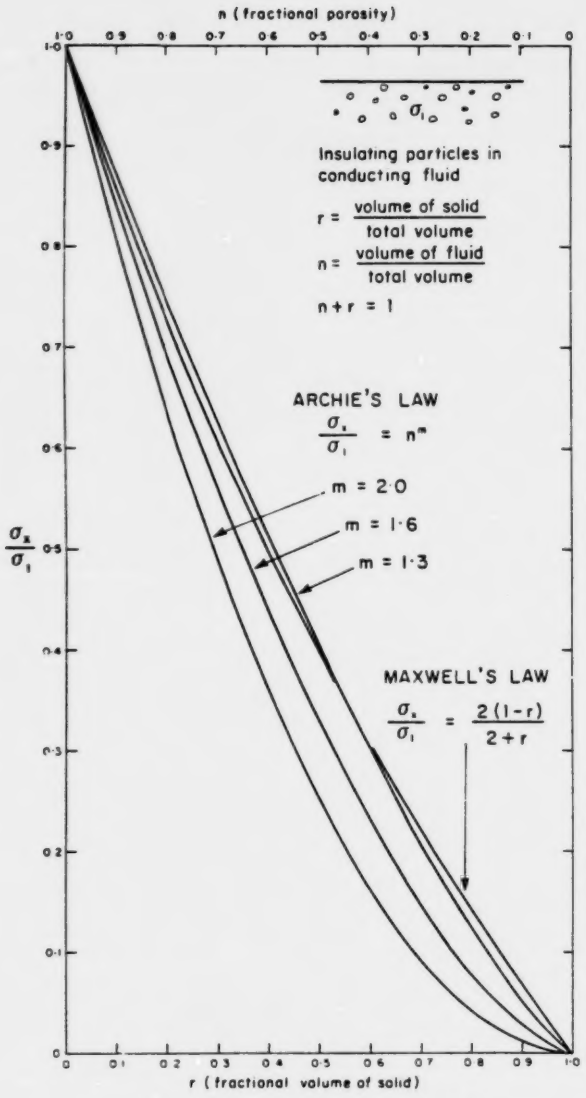

n (fractional porosity)
1·0 0·9 0·8 0·7 0·6 0·5 0·4 0·3 0·2 0·1 0
Insulating particles in conducting fluid
r = volume of solid / total volume
n = volume of fluid / total volume
n + r = 1
ARCHIE'S LAW
σx/σ1 = n^m
m = 2·0
m = 1·6
m = 1·3
MAXWELL'S LAW
σx/σ1 = 2(1-r)/2+r
σx/σ1
r (fractional volume of solid)

FIGURE 9. Graph of Archie's Law and Maxwell's Law.

Table 10 from which it is seen that except for very low moisture the relationship is essentially a square law with mosture content.

It has been suggested by Rhoades et al [17] that it might be possible to estimate the values of σ_s, a, and b on the basis of soil texture and mineralogy and, given a measurement of the bulk soil conductivity and the moisture content, to determine the conductivity of the fluid and thus salinity.

IV. 4. Electrical Layering Arising from Soil Moisture

From the preceding paragraphs we observe that, even if the soil material is physically homogeneous, for example consists of clean well-sorted silt, as soon as we introduce soil moisture of finite electrical conductivity we have established a medium in which the electrical conducvitity can vary strongly with depth. Near surface where the moisture content is low the conductivity is also low. With

TABLE 10. Measured moisture content constants and surface conductivities (after J. D. Rhoades et al. [17])

Soil type	a	b	σ_s
			mmho/cm
Pachappa fsl	1.382	−0.093	0.18
Indio vfsl	1.287	−0.116	0.25
Waukena l	1.403	−0.064	0.40
Domino cl	2.134	−0.245	0.40

increasing depth the conductivity rises rapidly as the moisture films become continuous, then more slowly as the available pore volume starts to fill, eventually saturating with complete filling of the pores. This situation will be rendered even more complex if the porosity itself is, as is often the case, a function of depth as suggested by the profile of Figure 4.

IV. 5. Colloidal Conductivity

It will be recalled that for clays the cation exchange capacity (CEC) was a measure of the number of ions adsorbed to the surface of clay particles. When the clay particles are immersed in a liquid there is evidence to show that these adsorbed ions can partially dissociate themselves from the clay particles and become available for ionic conductivity. Since the ion exchange capacity of clays can be great due to their large surface area many ions may be supplied for electrical conductivity; the addition of a small amount of clay to an otherwise clean mixture can substantially increase the electrical conductivity.

The addition of clay appears to affect the electrical conductivity of the mixture in two ways. Repeating equation (10)

$$\sigma_x = \sigma_1\theta(a\theta + b) + \sigma_s \qquad (10)$$

the added ions increase the value of σ_1 above the value that the porewater would have in the absence of the clay. Furthermore although dry clay is highly resistive, as soon as a thin layer of moisture (perhaps only a few molecules thick) surrounds the clay particles ion movement across the surface of the clay particle within the cloud of adsorbed ions may occur. This surface contribution to the conductivity, essentially independent of the moisture content, is the second term in the equation. It will be most significant at low moisture contents.

The contribution to σ_1 from clay content will be most evident for soils in which the porewater is relatively pure (and therefore has low conductivity) and will be least effective in soils having highly saline porewater. For either contribution we should expect that clays with higher CEC will produce more conductive soils and a comparison of Table 11 with Table 2 shows that this is the case

In summary, in areas where the soil porewater is not particularly saline the electrical properties of the soil may be strongly influenced by and indeed in some cases completely dominated by the amount and type of clay minerals present. The possible influence of clay materials should always be kept in mind. It is also possible that a similar effect arises as a result of the colloidal properties of humus which might be important in tropical climates where the humus layer is well leached and contains few clay minerals.

IV. 6. Effects of Freezing on Soil Conductivity

Suppose that we take our tank, filled with a clean sand/water mixture, and start to lower the temperature. The electrical conductivity of the mixture will decrease in exactly the same way that the conductivity of the electrolyte does. When the temperature reaches 0°C the water freezes and since the conductivity of ice is extremely low the conductivity of the mixture falls essentially to zero.

Now suppose that in addition to the sand some clay is introduced to the mixture and the temperature is again reduced. As the temperature passes through 0°C some of the water freezes; however the

TABLE 11. Physical properties of typical Upland and Lowland soils in western Puerto Rico (after J. W. Walker et al. [18])

Topographic location	Sample no.	Moisture (%)	Conductivity (mmho/m)	Clastic material (%)	Clay fraction (%)	Clay type(s) (%)
Uplands	1	42	16.0	21	79	100% kaolinite
Uplands	2	46	1.2	42	58	100% kaolinite
Uplands	3	25	1.0	5	95	100% kaolinite
Lowlands	4	21	65.0	66	34	100% montmorillonite
Lowlands	5	32	169.0	39	61	60% montmorillonite 40% kaolinite
Lowlands	6	25	269.0	15	85	90% montmorillonite 10% kaolinite

electrical field of the adsorbed ions on the clay particles locally orients the neaby water molecules to prevent their freezing [17]. Furthermore as the solvent freezes there is a tendency for the impurity ions to stay within the liquid fraction and the actual electrical conductivity of the remaining liquid water increases with decreasing temperature. The net result is that mixtures containing clay or silts tend to have an electrical conductivity which decreases relatively slowly with temperature as the temperature passes through 0°C and indeed to retain a moderate conductivity even at temperatures well below freezing as illustrated in Figure 10.

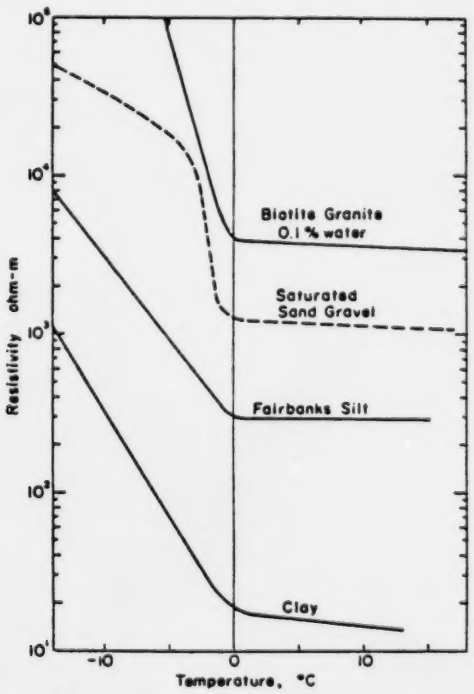


FIGURE 10. Resistivities for several soils and one rock type as a function of temperature (after Hoekstra and McNeill [20]).

IV. 7. Electrical Properties of Rocks

As with unconsolidated materials the matrix of most water-bearing rocks is insulating and the electrical conductivity is also electrolytic. A major difference between unconsolidated sediments and rocks lies in the types of pore geometries. For example in sedimentary rocks the porosity is generally inter-granular and consists of voids still remaining from the compaction process. In igneous rocks the porosity of the rock itself may be extremely small, however moisture circulates through fractures in the rock which are the result of mechanical breakage. These cracks are called joints and may be sufficiently large and/or numerous that their presence completely dominates the electrical conductivity. Such jointing may also play a major role in the conductivity of the more impermeable sedimentary rocks. When large joints are present the local conductivity may be expected to vary strongly with position. A third form of porosity which may not make a major contribution to electrical conductivity as normally measured is vugular porosity. It consists of cavities (as might be caused by solutions circulating in limestone) interconnected by small pores which dominate the D.C. electrical behavior. It should be noted that in the case of electromagnetic excitation of currents direct electrical (ohmic) inter-cavity connection is not necessary and appreciable response to this excitation may come from the fluid in each cavity separately.

Table 12 illustrates normal porosity for various rock types. It is seen that the total porosity can be very small, of the order of a few percent, and we would therefore expect, particularly for unfractured Precambrian igneous rocks and high-ranking metamorphosed rocks, the electrical conductivity to be very low, as is generally the case. On the other hand shales may be relatively porous and in addition the conductivity of the pore water may be high as a result of ion exchange effects. For this reason shales can be as conductive as 30 to 40 millimhos per meter and in some cases even higher.

Since in general the porosities are smaller for consolidated materials and furthermore at this end of the scale the various exponents in Archie's Law have a large effect, it is difficult to predict the electrical properties of any given rock type.

There is another feature which occurs in sedimentary rocks and which is of importance in determining their electrical characteristics. Being depositional in nature these rocks are layered and the electrical conductivity perpendicular to the bedding planes may be less than the conductivity parallel to the planes.

This feature is illustrated in Table 13 which lists the coefficient of anisotropy for various layered rocks. The coefficient is defined in Figure 11.

Another type of rock conductor called a structural conductor [21] occurs as a result of fracturing and is often linear in shape. Such conductors arise in the interior of faults, shear zones, contact frac-

TABLE 12. Normal ranges in porosity for rocks (after Keller and Frischknecht [5])

Rock type	Intergranular porosity (%)	Joint porosity (%)	Vugular porosity* (%)
Paleozoic sandstones and shale	5–30	0–1	0
Paleozoic limestones	2–10	0–2	0
Paleozoic clastic volcanics	5–30	0–2	0
Post Paleozoic sandstones and shale	10–40	0	0
Post-Paleozoic limestones	4–20	0–2	0
Post-Paleozoic clastic volcanics	10–60	0	0
Precambrian sediments and low-rank metamorphosed sediments	1–8	0–2	0
Precambrian igneous rocks and high-rank metamorphic rocks	0–2	0–2	0
More recent igneous rocks	0–10	0–2	0

*Vugular porosity accounts for an appreciable total porosity only in rare cases.

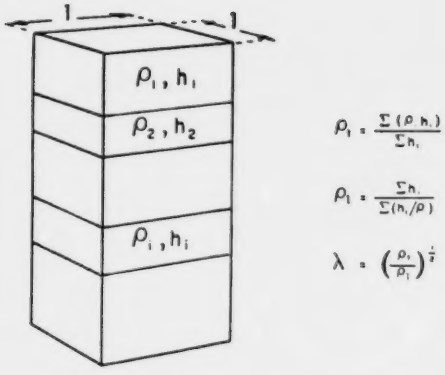


FIGURE 11. Definition of coefficient of anisotropy (λ) for layered sediments (after Keller and Frischknecht [5]).

TABLE 13. Coefficients of anisotropy for layered rock (after Keller and Frischknecht [5])

Rock type	Coefficient of anisotropy
Volcanic tuff, Eocene and younger, from Nevada	1.10–1.20
Alluvium, thick sections from the southwestern United States	1.02–1.10
Interbedded limestones and limey shales from northeastern Colorado	2.0 –3.0
Interbedded anhydrite and shale, northeastern Colorado	4.0 –7.5
Massive shale beds	1.01–1.05
Interbedded shale and sandstone	1.05–1.15
Baked shale or low-rank slate	1.10–1.60
Slates	1.40–2.25
Bitumenous coal and mudstone	1.7 –2.6
Anthracite coal and associated rocks	2.0 –2.6
Graphitic slate	2.0 –2.8

ture zones, etc., where the rock material has been ground into small particles which allows increased circulation of groundwater resulting in enhanced weathering to produce clay minerals. Structural conductors occur in a wide range of sizes.

V. EXAMPLES OF CONVENTIONAL MEASUREMENTS OF SOIL AND ROCK RESISTIVITIES

The material in this section gives a broad indication as to the range of resistivity or conductivity which might be encountered in various terrain materials in various climatic zones. Extreme caution must be exercised in employing these values for anything other than a rough guide as to anticipated survey results.

As an introduction Table 14 illustrates the resistivities of igneous and metamorphic rocks as given by Telford et al [22]. Table 15 lists resistivities of sediments from the same source. Table 6, from Heiland [14], lists the ratio ρ_s/ρ_0 as defined in Section IV for various consolidated and unconsolidated materials.

V. 1. Temperate Zones

Table 16 records the ranges of resistivity compiled for different terrain materials from a variety of survey and laboratory measurements, from Culley et al [23].

Table 17 from Sellman et al [24] shows survey data over different soil types made with three different measurement techniques (i) radio-frequency magneto-telluric at approximately 300 kHz, (ii) low-frequency magnetically induced currents using dipole transmitter and receiver at 10 kHz, and (iii) standard Wenner array at DC. The measured resistivities are relatively independent of the method of measurement; the general trend of increasing resistivity with particle size should be noted.

A complete set of measurements by Smith-Rose [25] on a variety of soils from different depths, with different moisture contents, and measured at various frequencies, shows that at the lower frequencies (i.e. between 1 and 100 kHz) the conductivity of soils is essentially independent of frequency. At higher frequencies the conductivity rises and the increase in conductivity is generally greatest for the most poorly conducting samples. The results of his laboratory measurements on soil samples taken from various parts of England are illustrated in Table 18 and profiles of conductivity with depth

TABLE 14. Resistivities of igneous and metamorphic rocks (after W. M. Telford et al. [22])

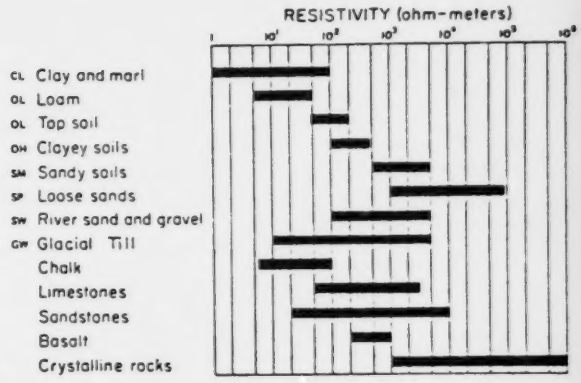
Rock type	Resistivity range (Ωm)
Granite	3×10^2–10^6
Granite porphyry	4.5×10^3 (wet)–1.3×10^6 (dry)
Feldspar porphyry	4×10^3 (wet)
Albite	3×10^2 (wet)–3.3×10^3 (dry)
Syenite	10^2–10^6
Diorite	10^4–10^5
Diorite porphyry	1.9×10^3 (wet)–2.8×10^4 (dry)
Porphyrite	10–5×10^4 (wet)–3.3×10^3 (dry)
Carbonatized porphyry	2.5×10^3 (wet)–6×10^4 (dry)
Quartz porphyry	3×10^2–9×10^3
Quartz diorite	2×10^4–2×10^6 (wet)–1.8×10^6 (dry)
Porphyry (various)	60–10^4
Dacite	2×10^4 (wet)
Andesite	4.5×10^4 (wet)–1.7×10^2 (dry)
Diabase porphyry	10^3 (wet)–1.7×10^5 (dry)
Diabase (various)	20–5×10^7
Lavas	10^2–5×10^4
Gabbro	10^3–10^6
Basalt	10–1.3×10^7 (dry)
Olivine norite	10^3–6×10^4 (wet)
Peridotite	3×10^3 (wet)–6.5×10^3 (dry)
Hornfels	8×10^3 (wet)–6×10^7 (dry)
Schists (calcareous and mica)	20–10^4
Tuffs	2×10^3 (wet)–10^5 (dry)
Graphite schist	10–10^2
Slates (various)	6×10^2–4×10^7
Gneiss (various)	6.8×10^4 (wet)–3×10^6 (dry)
Marble	10^2–2.5×10^8 (dry)
Skarn	2.5×10^2 (wet)–2.5×10^8 (dry)
Quartzites (various)	10–2×10^8

TABLE 15. Resistivities of sediments (after W. M. Telford et al. [22])

Rock type	Resistivity range (Ωm)
Consolidated shales	20–2 × 10^3
Argillites	10–8 × 10^2
Conglomerates	2 × 10^3–10^4
Sandstones	1–6.4 × 10^8
Limestones	50–10^7
Dolomite	3.5 × 10^2–5 × 10^3
Unconsolidated wet clay	20
Marls	3–70
Clays	1–100
Alluvium and sands	10–800
Oil sands	4–800

from these measurements are shown in Figure 12. It is seen from Table 18 that the soil type varies rapidly with depth, as does the soil moisture content; both of these influence the conductivity profiles. Smith-Rose concludes that clays have the highest conductivities, greater than 10 millimhos per meter, loams and chalks are of the order or 10 millimhos per meter and sandy or gritty soils are appreciably less. He also points out that a diurnal temperature range of 20°C at the surface of the soil represents a temperature change of approximately 1.4°C at a depth of one foot. Measurements made on a soil sample at 1.2 MHz as a function of moisture content by weight show a conductivity that increases approximately as the square of the moisture content.

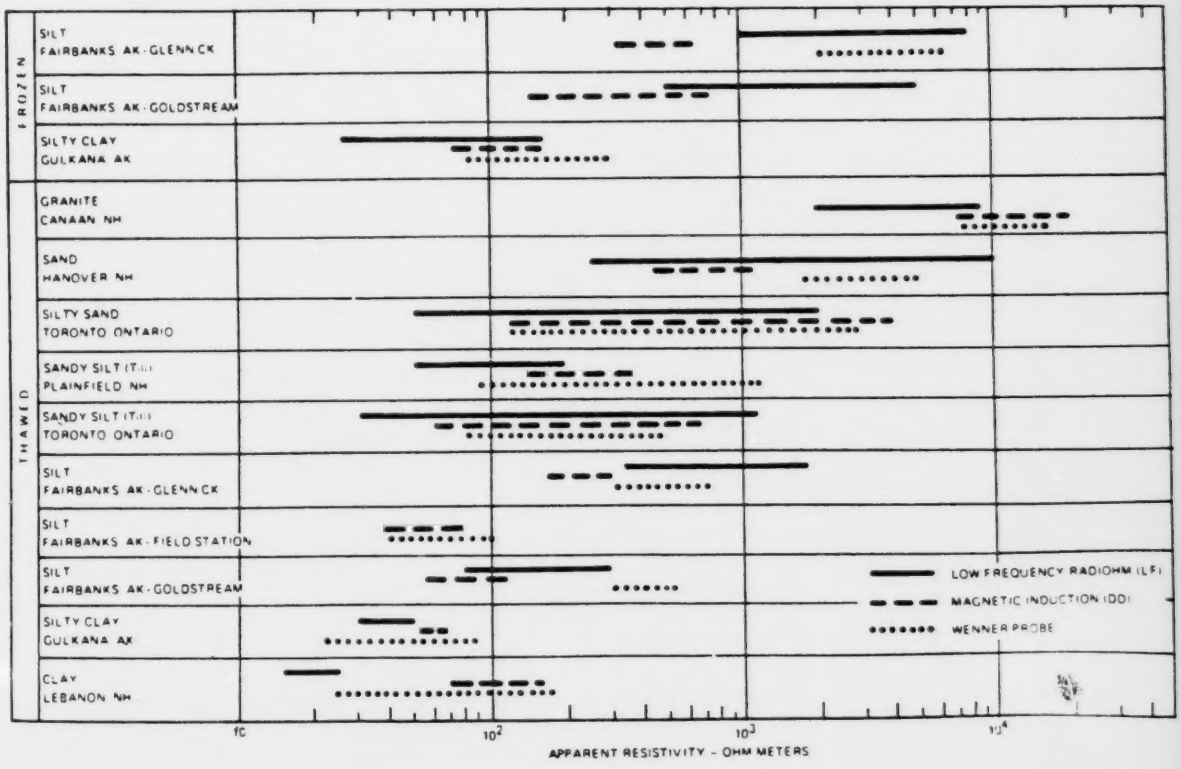
TABLE 16. Resistivity ranges for various terrain materials (after Culley et al. [23])



V. 2. Tropical Humid Zones [26]

The examples given above have been taken from temperate zone soils and seem to be fairly representative. In the case of soils occurring in tropical humid climates (annual temperatures of the order of 25°C; annual precipitation of greater than a meter, generally falling during a part of the year) the weathering can be very deep. Indeed, unweathered parent rock may not occur until 30 meters in flat country, 60 meters in hilly country and in rare occasions depths

TABLE 17. Apparent resistivity data obtained for various material types using three measuring techniques (after Sellman et al. [24])



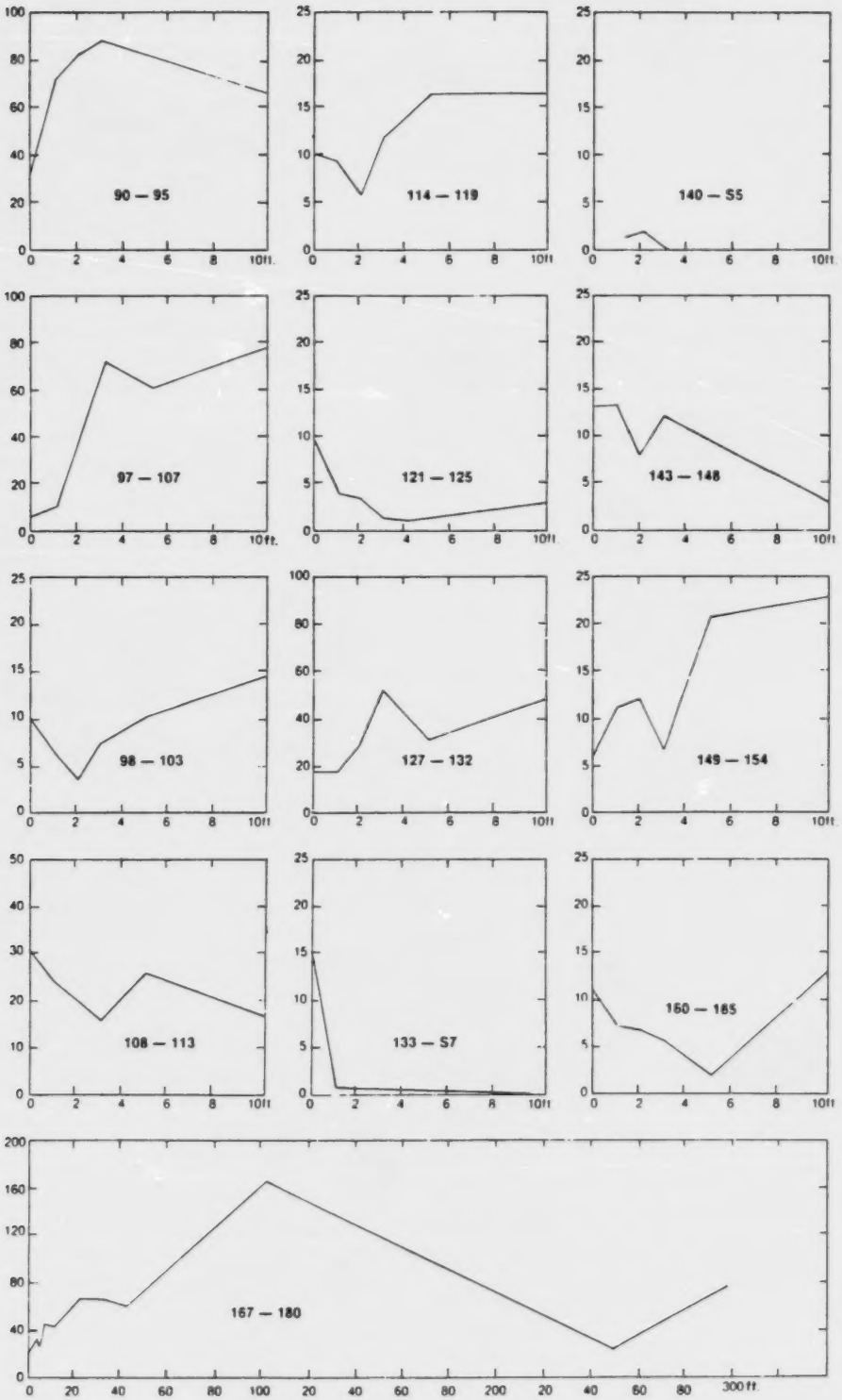


FIGURE 12. Plots of conductivity (mmhos/m) versus depth (feet) for data in Table 18.

TABLE 18. Measurements of samples of soil taken from different depths at various sites (after R. L. Smith-Rose [25])

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity at 20°C Millimho/m	
						1 kHz	100 kHz
			ft.		per cent		
90	Rugby Radio	Lower lias	Surface	Dark fibrous loam	60	33	38
92	Station (1)		1	Loam and clay	33	72	78
93			2	Clay and sand	26	83	89
94			3	Blue clay	25	89	100
95			10	Blue clay	23	67	72
97	Rugby Radio	Lower lias	Surface	Loam	22	6.1	7.2
104	Station (2)		1	Loam and clay	13	9.4	9.4
105			3	Blue clay	27	72	83
106			5	Clay and sand	21	61	61
107			10	Blue clay	25	78	89
98	Baldock, Herts	Chalk	Surface	Fibrous loam	21	9.4	10.0
99	(P.O. Receiving Station)		1	Chalky loam	21	6.1	6.1
100			2	Chalk	24	8.1	2.9
101			3	Chalk	27	7.2	7.8
102			5	Chalk	26	10.1	15.6
103			10	Chalk	27	14.4	15.6
108	Tatsfield, Kent	Upper	Surface	Fibrous loam	37	30	38
109	(B.B.C. Receiving Station)	greensand	1	Brown, sandy clay	1	24	27
110			2	Brown sand	15	20	22
111			3	Light brown sand	13	15.6	10.7
112			5	Light brown sand	20	26	26
113			10	Yellow sand	15	16.7	19
114	Brookmans Park, Herts	London	Surface	Fibrous loam	19	10.0	10.6
115	(London Regional Station)	clay	1	Stony loam	18	9.4	10.0
116			2	Light sandy clay	22	5.6	7.2
117			3	Sandy clay	22	12.2	13.3
118			5	Sandy clay	21	16.7	18.8
119			8 to 10	Clay and shingle	10	16.7	17.8
121	Daventry	Upper lias	Surface	Fibrous loam	28	9.4	10.6
122	Northants		1	Sandy loam	16	3.8	3.8
123			2	Brown sand	14	3.2	3.2
124			3	Brown sand	5.0	1.1	1.2
126			5	Sand and sandstone	8.5	0.8	1.0
125			10	Sand and sandstone	24	2.9	3.7
127	Washford Cross, Somerset	Red Marls	Surface	Reddish-brown loam	23	16.7	18.9
128	(West Regional Station)		1	Reddish-brown clay	20	16.7	18.9
130			2	Reddish-brown clay	18	28.9	31
129			3	Reddish-brown clay	21	52	54
131			5	Reddish-brown clay	19	31	34
132			10	Reddish-brown clay	15	48	50
133	Brendon Hills, Somerset	Devonian	Surface	Black fibrous loam	210	14.4	16.7
134			1	Loam and slate	9.0	0.3	0.3
135			2	Loam and slate	9.0	0.2	0.2
136			3	Loam and slate	8.0	0.1	0.1
137			5	Loam and slate	5.5	0.0	0.0
S.7			10	Slate	—	0.0	0.0
140	Merrivale, Dartmoor, Devon	Granite	1	Gritty loam	18	1.3	1.3
141			2	Gritty loam	13	1.6	1.6
S.1			3 to 10	Granite	—	0.0	0.1
S.2			3 to 10	Granite	—	0.0	0.1
S.5			3 to 10	Granite	—	0.0	0.0
139	Dousland, Dartmoor, Devon	Devonian	Surface	Loam	47	6.1	6.7
142			1	Dark brown loam	41	2.7	2.7
S.4			Below 1	Slate	—	0.0	0.0
S.6			Below 1	Granite	—	0.0	0.0
143	Moorside, Edge, Yorks	Millstone grit	Surface	Fibrous loam	130	13.3	17.8
144	(North Regional Station)		1	Dark grey clay	60	13.3	15.6
145			2	Dark grey clay	35	7.8	10.6
146			3	Dark grey clay	39	12.2	16.7
147			5	Dark grey clay	19	9.4	11.1
148			10	Yellow and grey clay	15	3.4	3.7
149	Westerglen, Falkirk	Boulder	Surface	Fibrous loam	38	6.1	7.2
150	(Scottish Regional Station)	clay	1	Fibrous loam	30	11.1	11.1
151			2	Clay and loam	19	12.2	12.2
152			3	Dark grit and clay	18	6.7	7.8
153			5	Dark grit and clay	18	21	24
154			10	Dark grit and clay	15	23	26

(*continued over*)

TABLE 18. (*concluded*)

Sample No.	Site	Geological classification	Depth	Description of sample	Moisture content	Conductivity at 20°C Millimho m	
						1 kHz	100 kHz
			ft.		per cent		
160	Teddington, Middlesex	London	Surface	Fibrous loam	26	11.1	12.2
161	(N.P.L.)	clay	1	Sandy loam	20	7.2	7.8
162			2	Sandy loam	13	6.7	7.2
163			3	Fine gravel	6.5	5.6	6.7
164			5	Coarse gravel	2.9	1.9	2.0
166			7	Fine sand	2.6	1.6	1.6
165			10	Sand and shingle	20	13.3	15.6
167	Wychbold, Droitwich	Red Marls	1	Red clay and loam	15	16.7	20
168	(Midland Regional Station)		2	Red clay	13	34	32
169			3	Red clay	14	23	24
170			5	Red clay and stones	15	43	51
171			10	Red clay and stones	21	41	44
172			20	Red clay suspension	31	67	78
173			30	Red clay suspension	41	67	78
174			40	Red clay suspension	25	61	72
175			50	Red clay	27	78	83
176			100	Grey clay and salt	28	177	233
177			150	Red clay and salt	27	—	—
178			200	Red clay and salt	24	—	—
179			250	Red clay and salt	22	24	26
180			300	Red clay and salt	31	73	89

of 250 meters have been observed. The resulting soils are red to yellow, soft with a high clay content, and with a specific gravity approximately one-half of that of the parent rock. Compared with the soils of temperate climates they are thick, humus poor, permeable, and have a high clay-silt ratio. Although the clay content is high this is somewhat compensated for by the fact that in well drained soils the clays are kaolinitic and the cation exchange capacity is less than in temperate zones (see Table 11). Iron-rich concretionary horizons called laterites form as a result of reprecipitation. These are hard, permeable, and if dry are usually very resistive.

The nature and the extent of the soil formation is a function of the rock type, texture, jointing, surface relief, vegetation, water-table, and micro-climate. For example, the relative absence of silt is due to the fact that fine-grained rocks weather faster than coarse-grained rocks; the abundance of clay results from the fact that it is a stable mineral.

An excellent series of measurements of the electrical properties of the weathered zones in tropical climates has been carried out by Palacky and Kadekaru in Brazil [27]. The measurements were done with conventional resistivity techniques and many soundings were taken. The results gave good agreement with a three-layered earth model and are summarized in Table 19. In general a resistive soil, relatively thin, is situated on top of a thick quite conductive weathered zone, in turn situated on the relatively resistive parent rock.

V. 3. Tropical Arid Zones

It is in tropical arid zones that the most conductive soils are encountered. As for humid zones the weathered layer can be many tens of meters in thickness, however in arid climates this material often contains a high salt concentration due to evaporation. Whereas the surface materials are usually dry, possibly lateritic, and resistive, deeper material may approach resistivities of the order of 1 ohm-meter. Furthermore substantial lateral variations of resistivity are not uncommon.

In the humid tropical zones referred to above the conductivity of the intermediate zone was due to the presence of an abundance of colloidal particles with moderate ion exchange capacities; abundant rainfall means that drainage patterns are well established and soil salts have long since been leached into major river channels and

TABLE 19. Tropical resistivity profiles (after Palacky and Kadekaru [27])

	Site	Soil		Weathered Zone		Bedrock	
		Thickness (meters)	Resistivity (ohm-meters)	Thickness (meters)	Resistivity (ohm-meters)	Type	Resistivity (ohm-meters)
Humid Tropical	Nova Lima	5–10	2000–15000	20–80	50–100	schists	∞
					200–400	granodiorite	∞
	Canabrava	5	90	3–18	15–27	basic	∞
		5	360	12–30	3–12	ultrabasic	∞
	Santa Fé	3	11000–18000	35	80–100	dunite	∞
	Quatipuro	0–1	200	15–35	10–30	phyllites	∞
			300–700	3–8	35–20	serpentinites	> 300
Arid Tropical	Santa Luz	-		3.5	65	granite	910
		1	120	10–20	13	basic volcanic	∞
	Curaça	-		6–10	20–35	amphibolites	1200
				15–20	80–130	gneiss	2000

TABLE 20. Diagnostic criteria for distinguishing between unaffected soil sites and encroaching and developed saline seeps (after Rhoades and Halvorson [28])

Site type	Salt content	Water content	Soil electrical conductivity
Unaffected	Low, increasing with depth	Low, increasing with depth	Low, increasing with depth
Encroaching saline seep	Low, increasing to a peak at a relatively shallow depth, then decreasing with further depth	Moist surface, becoming wet with depth	Intermediate, increasing to a peak at a relatively shallow depth, then decreasing with further depth
Developed saline seep	High, decreasing with depth	Relatively uniformly wet to the water table	High, decreasing with depth

thence into the oceans. In hot arid climates drainage patterns are poorly established and drainage basins may have no outlet to permanent streams. Salt-bearing waters drain from topographically high regions into lower areas where the water evaporates, leaving a high residual salt content, largely a reflection of the imperfect drainage channels.

The occasional addition of water might be due either to precipitation or irrigation. In the cultivated dry land soils of the northern Great Plains the near surface (plant root-zone) is leached with essentially pure water derived from rain and snow melt during the wet months. Rhoades and Halvorson [28] discuss how this results in a soil salinity concentration which increases with depth. However during the summer months when a saline water table in this climate is situated within approximately one meter from the surface an upwards flow of moisture is caused by evaporation at the soil surface and transpiration within the root zone. This upwards flow reverses the original leaching which transported salts downwards and causes them to ascend so that a concentration peak can form in the soil salinity profile. The soils can remain excessively wet as a result of the hygroscopic nature of the salts and because the salts reduce the effective use of water by plants via evapo-transpiration. Rhoades defines such a condition as a "saline seep" and notes that it can form without the water table actually emerging at the surface. As this seep develops the peak in the soil salinity profile moves upwards until it finally appears at or near the surface as indicated in Table 20 which illustrates the various conditions that can exist in a region which sees seasonal precipitation followed by seasonal drought. Figure 13 illustrates vertical profiles of resistivity versus depth as determined by an expanding Wenner array for the three conditions described in Table 20.

For saline soils, the contribution to conductivity from salt concentration generally outweighs that from cation exchange capacity and the conductivity is relatively independent of clay content.

The effect of weathered-zone salinity is probably at its worst in western Australia where the zone is often 100 meters in thickness and has been known to exceed 300 meters. Hygroscopic salts maintain soil moisture at levels substantially above the water table and resistivities of the order of 1 ohm-meter have been observed. Large lateral variations result from the imperfect drainage patterns; slight changes in surface topography often show up as large changes in subsurface conductivity. A lateritic hard pan is not unusual on the surface. This layer is extremely resistive and completes the complexity and difficulty of making conventional electrical measurements in this environment.

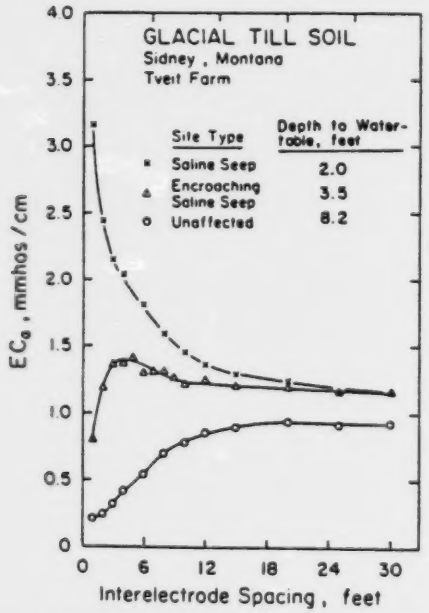


FIGURE 13. Relation between soil electrical conductivity, EC_a, and interelectrode spacing for a saline seep, an encroaching saline-seep site, and an unaffected site for glacial till-clay loam soil near Sidney, Montana (after Rhoades and Halvorson [28]).

V. 4. Arctic Zones

Finally we turn our attention to arctic regions in which permafrost is a major consideration. It should be noted that the definition of permafrost requires only that the mean annual temperature of the ground be less than 0°C for several years; the definition is completely independent of the nature of the material, the amount of moisture, and indeed whether or not the moisture is frozen. In

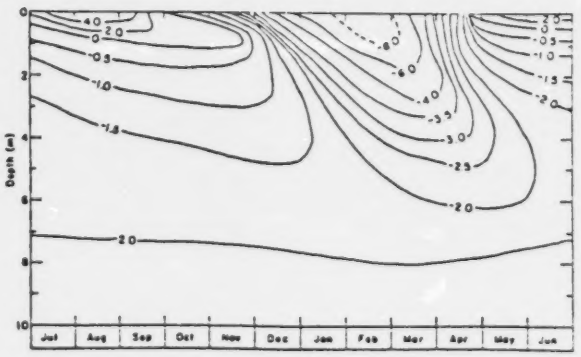


FIGURE 14. Vertical and temporal temperature variations – contoured in °C (after Arcone et al [29]).

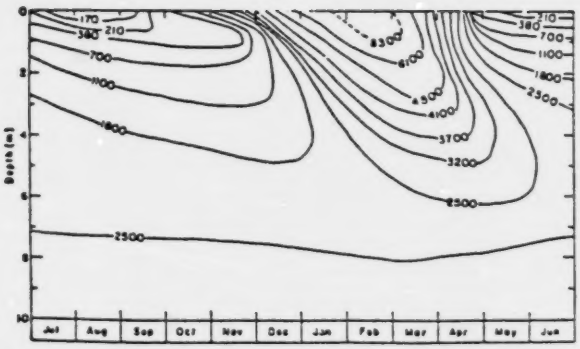


FIGURE 15. Computed vertical and temporal resistivity variations from data of Figure 14 – contoured in ohm-meters (after Arcone et al [29]).

northern climates we find that mineralogy, porosity, free water content, and ionic concentration within the free water are important resistivity factors as they are for temperate zones. In permafrost regions we have the additional complexity that small changes in temperature of the ground near 0°C may exert a large influence on terrain conductivity. The effect depends on the nature of the material and also the moisture content since as we have seen earlier even at temperatures substantially below 0°C considerable moisture may remain unfrozen in the case of clays whereas in the case of coarser material virtually all will be frozen. In short, ice content is a complicated function of many variables.

As an example of electrical layering arising due to temperature only consider Figure 14 which illustrates annual variations in ground temperature recorded near Fairbanks, Alaska. The region is in a discontinuous permafrost zone and subsurface material consists primarily of perennially frozen organic silt containing a varying amount of ground ice. From laboratory measurements on saturated organic silt to determine the variation of electrical resistivity with temperature, a plot of electrical resistivity with depth and time was derived [23] and is shown in Figure 15. We see from this figure that a resistivity range of 50 to 1 can occur as a result of temperature changes alone.

In the discontinuous zone of permafrost subsurface temperatures are subtly influenced by many variables and even in ground which is

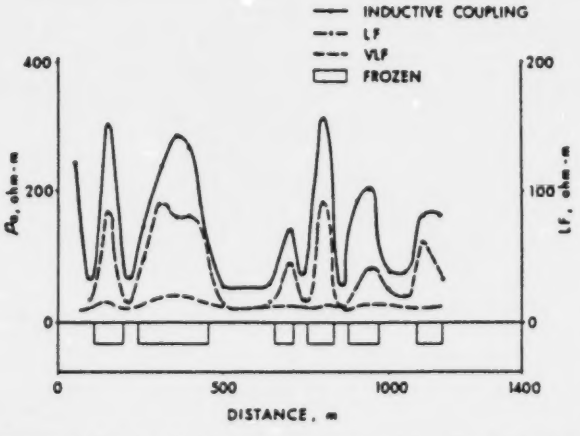


FIGURE 16. Results of the apparent resistivity measured with VLF (18.6 kHz), LF (375 kHz) radiohm and a magnetic induction instrument (EM31) over a section of shallow discontinuous permafrost (after P. Hoekstra [30]).

laterally uniform insofar as material type is concerned lateral temperature variations can bring about large changes in electrical resistivity as shown in Figure 16 where the survey traverse was taken over glacial lake basin sediments. The frozen areas outlined on the figure were derived from resistivity measurements and confirmed by drilling [24].

VI. SUMMARY

In this technical note we have discussed the concept of terrain conductivity, examined some of the properties of soils and rocks that affect their conductivity, and reviewed some measurements on typical terrain materials under a variety of climatic conditions.

To summarize, terrain conductivity is usually determined by one or more of the following parameters:

(1) clay content, clay type
(2) moisture profile with depth
(3) moisture salinity
(4) moisture temperature

Of these the most complex is usually the moisture profile, by which is meant the way in which (i) the porosity, (ii) the extent to which the pores are filled with water, and, (iii) the number, size and shape of interconnecting passages all vary with depth. The moisture profile is affected by material type (directly influencing porosity etc., or indirectly influencing permeability and water table location), topography (influencing the water table location), compaction (influencing porosity), and season (rates of precipitation, evaporation).

It is evident that many parameters may affect the ground conductivity. Fortunately at any given location relatively few are usually dominant however the survey interpreter should be aware of the possible alternatives. It is hoped that this brief treatment will be useful in assessing those parameters that are influential in the survey area and will thereby lead to a more accurate interpretation of survey data.

The bibliography gives a good indication of current interest in the electrical properties of rocks and soils and the curious reader will find much valuable material in the cited references.

BIBLIOGRAPHY

[1] Olhoeft, G.R. (1975) "Electrical Properties of Rocks". The Physics and Chemistry of Rocks and Minerals. pp 261–278. J. Wiley and Sons. N.Y.
[2] Olhoeft, G.R. (1977) "Electrical Properties of Natural Clay Permafrost". Can. J. Earth Sciences (14) pp 16–24.
[3] Ward, S.H., Fraser, D.C. (1967) "Conduction of Electricity in Rocks". Ch. 2. Mining Geophysics Vol. II. Society of Exploration Geophysicists, Tulsa, Oklahoma.
[4] Madden, T.R. (1976) "Random Networks and Mixing Laws". Geophysics (41, No. 6A) pp 1104–1125.
[5] Keller, G.V., Frischknecht, F.C. (1966) "Electrical Methods in Geophysical Prospecting". Ch. 1. Pergamon Press, N.Y.
[6] L.R. Webber, Ed. "Ontario Soils". Publication 492, Ministry of Agriculture and Food. Province of Ontario. Canada.
[7] Kirkham, D. (1964) "Soil Physics". Handbook of Applied Hydrology. Ch. 5. Chow, V.T., Ed. McGraw Hill. N.Y.
[8] Press, F., Siever, R. (1978) "Earth". Ch. 4. W.H. Freeman & Co., San Francisco.
[9] Maxey, G.B. (1964) "Hydrogeology". Handbook of Applied Hydrology. Ch. 4. Chow, V.T., Ed. McGraw Hill. N.Y.
[10] Millot, G. (1979) "Clay". Scientific American (240), 4, pp 109–118.
[11] Meyboom, P. (1967) "Hydrogeology". Groundwater in Canada. Ch. 2. Brown, I.C., Ed. Geol. Surv. Canada. Econ. Geol. Rept. 24.
[12] Todd, D.K. (1964) "Groundwater". Handbook of Applied Hydrology. Ch. 13. Chow, V.T. Ed. McGraw Hill. N.Y.
[13] Brown, I.C. (1967) "Introduction". Groundwater in Canada. Ch. 1. Brown, I.C., Ed., Geol. Surv. Canada. Econ. Geol. Rept. 24
[14] Heiland, C.A. (1968) "Geophysical Exploration". Ch. 10. Hafner Publishing Co. N.Y.
[15] Doherty, L.H. (1963) "Electrical Conductivity of the Great Lakes". J. Res. Natl. Bur. Stds. (67D), pp 765–771..
[16] Jackson, P.D., Taylor Smith, D., Stanford, P.N. (1978) "Resistivity –

Porosity – Particle Shape Relationships for Marine Sands". Geophysics (43) pp 1250–1268.
[17] Rhoades, J.D.; Raats, P.A.C.; Prather, R.S. (1976) "Effects of Liquid-Phase Electrical Conductivity, Water Content, and Surface Conductivity on Bulk Soil Electrical Conductivity". Soil Sci. Soc. of America Jour. (40) pp 651–665.
[18] Walker, J.W.; Hulse, W.H.; Eckart, D.W. (1973) "Observations of the Electrical Conductivity of the Tropical Soils of Western Puerto Rico". Geol. Soc. Amer. Bull. (84) pp 1743–1752.
[19] Olhoeft, G.R. Private Communication.
[20] Hoekstra, P.; McNeill, J.D. (1973) "Electromagnetic Probing of Permafrost". Proc. Second Intl. Conference on Permafrost. Yakutsk, USSR. pp 517–526.
[21] Grant, F.S.; West, G.F. (1965) "Interpretation Theory in Applied Geophysics". Ch. 13. McGraw Hill, N.Y.
[22] Telford, W.M.; Geldart, L.P.; Sheriff, R.E.; Keys, D.A. (1976) Applied Geophysics Ch. 5. Cambridge Univ. Press, N.Y.
[23] Culley, R.W.; Jagodits, F.L.; Middleton, R.S. (1975) "E-Phase System for Detection of Buried Granular Deposits. Symposium on Modern Innovations in Subsurface Exploration". 54th Annual Meeting of Transportation Research Board.
[24] Sellmann, P.V.; Arcone, S.A.; Delaney, A. (1976) "Preliminary Evaluation of New LF Radiowave and Magnetic Induction Resistivity Units – Over Permafrost Terrain". Natl. Res. Council Canada Tech. Mem. 119. Proc. Symposium on Permafrost Geophysics. 12 Oct.
[25] Smith-Rose, R.L. (1934) "Electrical Measurements on Soil with Alternating Currents". Proc IEE No. 75 pp 221–237.
[26] Meillon, J.J. (1978) "Economic Geology and Tropical Weathering". Can. Inst. Mining and Metallurgy (CIM) Bulletin, July. pp 61–69.
[27] Palacky, G.J.; Kadekaru, K. (1979) "Effect of Tropical Weathering on Electrical and Electromagnetic Measurements". Geophysics (44) pp 69–88.
[28] Rhoades, J.D.; Halvorson, A.D. (1977) "Electrical Conductivity Methods for Detecting and Delineating Saline Seeps and Measuring Salinity in Northern Great Plains Soils". Agricultural Research Service Dept. ARS W-42 U.S. Dept. of Agriculture, Western Region.
[29] Arcone, S.A.; Sellman, P.; Delaney, A. (1979) "Effects of Seasonal Changes and Ground Ice on Electromagnetic Surveys of Permafrost". USA CRREL Report. U.S.A. Cold Regions Research & Engineering Labs. Hanover, New Hampshire, U.S.A.
[30] Hoekstra, P. (1978) "Electromagnetic Methods for Mapping Shallow Permafrost". Geophysics (43) pp 782–787.

REFERENCES NOT CITED BUT USEFUL

[31] Morley, L.W., Ed. (1967) "Mining and Groundwater Geophysics". Geological Survey of Canada. Econ. Geol. Dept. No. 26.
[32] Wilcox, S.W. (1944) "Sand and Gravel Prospecting by the Earth Resistivity Method". Geophysics (9) pp 36–45.
[33] Kelly, S.F. (1962) "Geophysical Exploration for Water by Electrical Resistivity". Jour. New England Water Works Assoc. (76) pp 118–189.

APPENDIX B

Technical Note TN-6:

Electromagnetic Terrain Conductivity Measurements At Low Induction Numbers

(Source : McNeill, J.D., 1980. Geonics Ltd.)

I. INTRODUCTION

The measurement of terrain resistivity to map geology has been utilized for over half a century. Several shortcomings, however, have prevented this technique from being widely accepted for engineering purposes. The first of these is that conventional galvanic resistivity surveys require a relatively large amount of manpower to execute and are thus expensive. Secondly, the actual value of resistivity itself is seldom diagnostic; it is the lateral or vertical variations of resistivity which form the basis of any interpretation. However the high cost of resistivity surveying generally means that fewer measurements are made than would be desirable, with the result that either (i) the survey area is not made large enough to establish a reasonable background against which the anomalous areas are to be delineated or (ii) the anomalous area itself is obscure and lacks definition.

An additional problem inherent to conventional resistivity techniques is that although the effective depth of exploration is determined by the selected inter-electrode spacing, resistive inhomogeneities which are small compared to this depth but which are located near the potential electrodes can cause a significant error in the measurement. Such fluctuations in the measured results are truly geological "noise" because it is not possible to determine the physical size, resistivity contrast, or location of the source. As a result of such inhomogeneities resistivity profiles carried out at constant interelectrode spacing tend to be noisy, limiting the resolution in resistivity that can be achieved, even though the instrumentation itself is capable of producing much higher accuracy.

It was an awareness of both the advantages of resistivity for engineering geophysical surveys and the disadvantages of conventional resistivity techniques that led Geonics Limited to examine the possibility of employing electromagnetic (inductive) techniques as an alternative for resistivity surveys. With the development of the EM31 and the EM34-3 it is now possible to map terrain conductivity virtually as fast as the operator(s) can walk; furthermore the sample volume is averaged in such a manner as to yield unexcelled resolution in conductivity.

These patented instruments have been designed to cover the range of depths generally useful for engineering geophysics; the EM31, one-man portable, has an effective depth of approximately 6 meters and the EM34-3, two-man portable, has stepwise selectable depths from 7.5 meters to a maximum of 60 meters.

Typical applications for the EM31 and EM34-3 instrumentation are:

(i) Delineating regions of permafrost (frozen pore water)
(ii) Locating gravel
(iii) Extending known gravel deposits
(iv) Mapping saline intrusions
(v) Detecting cavities in carbonate rocks
(vi) Mapping pollution plumes in groundwater
(vii) Mapped bedrock topography
(viii) Mapping terrain conductivity for electrical grounding
(ix) General geological mapping (soil types, fault and fracture zones, etc.)
(x) Archaeological exploration
(xi) Locating pipes (EM31) and metallic-type conductors

This technical note describes both the principles and the instrumentation employed to measure terrain conductivity using electromagnetic techniques at low induction numbers. For a detailed discussion of the concept of terrain resistivity/conductivity and of the various factors that control this parameter the reader is referred to Geonics Limited Technical Note "Electrical Conductivity of Soils and Rocks".

II. PRINCIPLE OF OPERATION

The application of electromagnetic techniques to the measurement of terrain resistivity, or more properly, conductivity* is not new and excellent descriptions of this technique are given in the literature [1], [2].

*Conductivity is preferred with inductive techniques since the response is generally proportional to conductivity and inversely proportional to resistivity.

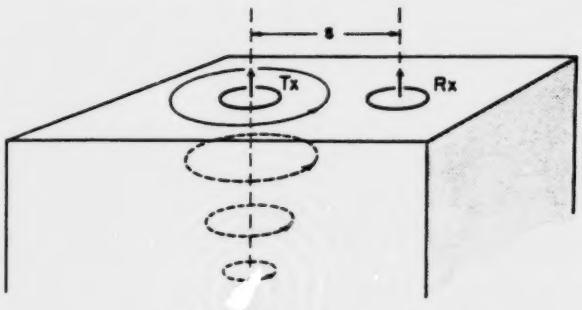


FIGURE 1. Induced current flow (homogeneous halfspace).

Consider Figure 1 in which a transmitter coil Tx energized with an alternating current at an audio frequency, is placed on the earth (assumed uniform) and a receiver coil Rx is located a short distance s away. The time-varying magnetic field arising from the alternating current in the transmitter coil induces very small currents in the earth. These currents generate a secondary magnetic field H_s which is sensed, together with the primary field, H_p, by the receiver coil.

In general this secondary magnetic field is a complicated function of the intercoil spacing s, the operating frequency, f, and the ground conductivity σ. Under certain constraints, technically defined as "operation at low values of induction number" (and discussed in detail in the appendix) the secondary magnetic field is a very simple function of these variables. These constraints are incorporated in the design of the EM31 and EM34-3 whence the secondary magnetic field is shown to be:

$$\frac{H_s}{H_p} \simeq \frac{i\omega\mu_o\sigma s^2}{4} \qquad (1)$$

where H_s = secondary magnetic field at the receiver coil
H_p = primary magnetic field at the receiver coil
$\omega = 2\pi f$
f = frequency (Hz)
μ_o = permeability of free space
σ = ground conductivity (mho/m)
s = intercoil spacing (m)
$i = \sqrt{-1}$

The ratio of the secondary to the primary magnetic field is now linearly proportional to the terrain conductivity, a fact which makes it possible to construct a direct-reading, linear terrain conductivity meter by simply measuring this ratio. Given H_s/H_p the apparent conductivity indicated by the instrument is defined from equation (1) as

$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right) \qquad (2)$$

The MKS units of conductivity are the mho (Siemen) per meter or, more conveniently, the millimho per meter.

III. INSTRUMENTATION

The EM31 (shown in Figure 2) has an intercoil spacing of 3.7 meters, which yields an effective depth of exploration of about 6 meters. The instrument can also be operated on its side, in which

FIGURE 2. EM31 in field operation.

case as will be seen in Section IV., the effective depth of exploration is reduced to approximately 3 meters. The instrument is one-man portable and can be used either in "station-by-station" mode or read continuously. The presence of layering in the earth can be detected by raising the instrument and noting the readings as a function of instrument height. If the earth is two-layered the conductivity of both layers and the upper layer thickness can be resolved.

The EM34-3 which is two-man portable has the two coils flexibly connected (Figure 3). The intercoil spacing is measured electronically so that the receiver operator simply reads a meter to accurately set the coils to the correct spacing, which can be 10, 20, or 40 meters so as to directly vary the effective depth of exploration as shown in Table 1.

FIGURE 3. EM34-3 in field operation.

TABLE 1. Exploration depths for EM34-3 at various intercoil spacings

Intercoil Spacing (meters)	Exploration Depth (meters)	
	Horizontal Dipoles	Vertical Dipoles
10	7.5	15
20	15	30
40	30	60

To measure terrain conductivity the transmitter operator stops at the measurement station; the receiver operator moves the receiver coil backwards or forwards until his meter indicates correct intercoil spacing and he reads the terrain conductivity from a second meter. The procedure takes 10 to 20 seconds. The coils are normally carried with their planes vertical (horizontal dipole mode) since in this configuration the measurement is relatively insensitive to misalignment of the coils. In the event that the greater depth of penetration resulting when the two coils are in the vertical dipole mode is desired, more care must be taken with intercoil alignment. Because of the relatively short intercoil spacing correct alignment is usually not difficult to achieve.

Both instruments are calibrated to read terrain conductivity in millimhos per meter. To convert these readings to resistivity (in ohmmeters) one simply divides them into 1,000, i.e. 50 millimhos per meter is the equivalent of 20 ohmmeters.

IV. SURVEY TECHNIQUES AND INTERPRETATION

For either the EM31 or EM34-3 it can be shown that in a homogeneous or horizontally stratified earth the current flow is entirely horizontal. Furthermore under the constraints by which the instruments are designed the current flow at any point in the ground is independent of the current flow at any other point since the magnetic coupling between all current loops is negligible. Finally, under these constraints the depth of penetration is limited only by the intercoil spacing. We say that the depth of penetration is "source" or "geometry" limited rather than "skin depth" limited since it is now controlled by the fall-off with distance of the dipolar transmitter field. For this reason all dimensions are normalized with respect to the intercoil spacing in subsequent sections of this technical note.

IV. 1. Instrumental Response as a Function of Depth (Homogeneous Halfspace)

Consider a homogeneous halfspace on the surface of which is located an EM31 or an EM34-3 transmitter as shown in Figure 4. Fixing our attention on a thin layer of thickness dz at depth z (where z is the depth divided by the intercoil spacing s) it is possible to calculate the secondary magnetic field in the receiver coil arising from all of the current flow within this or any other horizontal thin layer. One can thus construct the function $\phi_v(z)$ shown in Figure 4 which describes the relative contribution to the secondary magnetic field arising from a thin layer at any depth z. We see from this figure that material located at a depth of approximately 0.4 s gives maximum contribution to the secondary magnetic field but that material at a depth of 1.5 s still contributes significantly. It is interesting to note that the ground at zero depth, i.e. the near surface material,

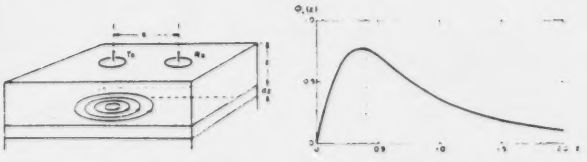


FIGURE 4. Relative response versus depth for vertical dipoles. $\phi_v(z)$ is the relative contribution to H_s from material in a thin layer dz located at (normalized) depth z.

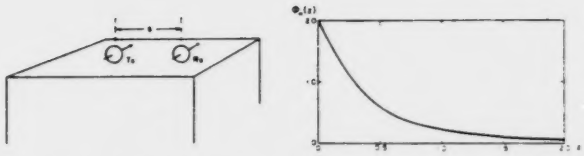


FIGURE 5. Relative response versus depth for horizontal dipoles

makes a very small contribution to the secondary magnetic field and therefore this coil configuration is insensitive to changes in near surface conductivity.

Figure 5 illustrates the function of Figure 4 for the case of both transmitter and receiver dipoles horizontal coplanar rather than vertical coplanar. For the coil configuration of Figure 5 (commonly used for the EM34-3 since it is less critical to intercoil alignment) the relative contribution from material near-surface is large and the response falls off monotonically with depth.

A comparison of the function ϕ for both coil configurations in Figure 6 emphasizes the different manner in which they respond to material at different depths. The difference is important since either instrument can be rolled over so that the vertical dipole transmitter/receiver geometry becomes a horizontal dipole transmitter/receiver geometry and vice versa. As will be seen later, this feature is useful in diagnosing and defining a layered earth. The figure also shows that for regions greater than one intercoil spacing in depth the vertical transmitter/receiver dipole gives approximately twice the relative contribution of the horizontal transmitter/receiver dipole.

To summarize, with either horizontal or vertical transmitter/receiver dipole orientation it is possible to construct a function which gives the relative response to the secondary magnetic field at the receiver from a thin layer of ground at any depth. That this is possible arises from the fact that (i) all current flow is horizontal and (ii) all current loops are independent of all other current loops. It should be noted that it is not possible to construct such functions for conventional resistivity techniques.

Finally, since as shown in Section II the definition of apparent conductivity is given in terms of the secondary magnetic field at the receiver, the functions in Figure 6 also give the relative contribution from material at different depths to the *apparent conductivity* indicated by the instrument meter. The integral of either function from zero to infinity gives the total secondary magnetic field at the receiver coil from a homogeneous halfspace which is directly related to the electrical conductivity of the halfspace by equation (1). It is therefore possible to state with great precision the relative influence of material at different depths to the indicated apparent conductivity.

IV. 2. Multi-Layered Earth Response

The functions shown in Figure 6 are useful for describing the relative sensitivity of either of the two coil configurations to material at various depths. However a function derived from them is more useful for performing calculations. It is defined as the relative contribution to the secondary magnetic field or apparent conductivity from all material below a depth z and is given by

$$R_{\substack{v\\H}}(z) = \int_z^\infty \phi_{\substack{v\\H}}(z)dz \qquad (3)$$

Called the cumulative response, this function is illustrated in Figure 7 for vertical coplanar transmitter/receiver dipoles. The figure shows, for example, that for this configuration all material below a depth of two intercoil spacings yields a relative contribution of approximately 0.25 (i.e. 25%) to the secondary magnetic field at the receiver coil.

Suppose now that our homogeneous halfspace has a conductivity of 20 millimhos per meter (50 ohmmeters). The equipment having been calibrated according to equation (2), the output meter indicates 20 millimhos per meter. From Figure 7 we observed that the material below two intercoil spacings contributed 25% to the secondary magnetic field and therefore 25% to the indicated meter reading. Suppose that we replace this deep material with an infinitely resistive (zero conductivity) substance. Since we have reduced to zero the 25% that this material contributed to the meter reading the new reading will be 75% of 20, or 15 millimhos per meter. Conversely, if we leave all of the material below two intercoil spacings at 20

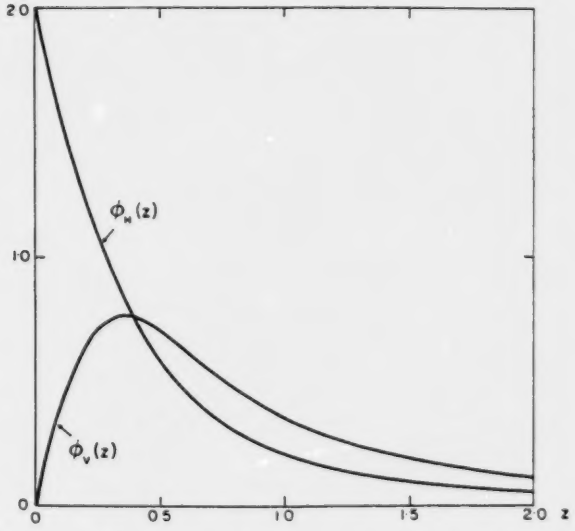


FIGURE 6. Comparison of relative responses for vertical and horizontal dipoles.

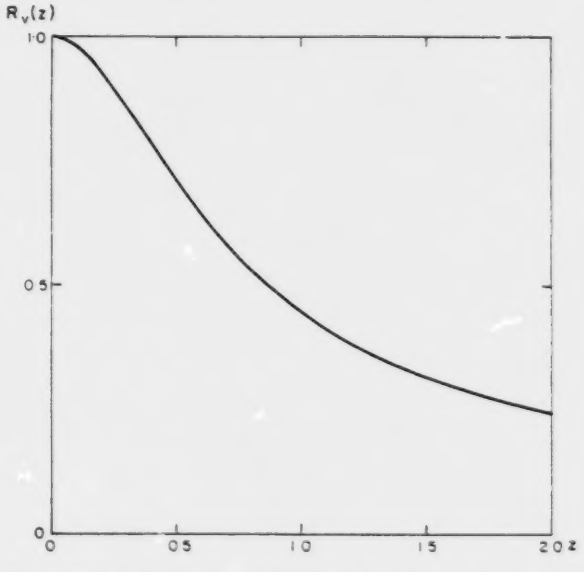


FIGURE 7. Cumulative response versus depth for vertical dipoles. $R_v(z)$ is the relative contribution to H_s from all material below a (normalized) depth z.

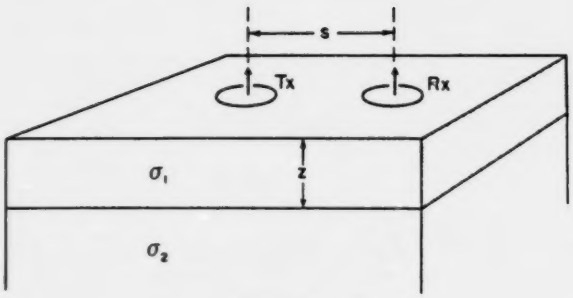


FIGURE 8. Two layer earth model.

millimhos per meter but make all material above two intercoil spacings infinitely resistive the meter reading will fall from the original 20 millimhos per meter for the homogeneous half space to 5 millimhos per meter, since, if all of the material below two intercoil spacings contributed 25% of the meter reading, all of the material above two intercoil spacings must contribute 75%; when removed the meter reading becomes 0.25 × 20 or 5 millimhos per meter.

From this example we see that there is a simple way to calculate the instrument reading on an arbitrarily layered earth as long as the intercoil spacing is much less than the skin depth in all of the layers. We simply add the contribution from each layer independently, weighted according to its conductivity and depth according to Figure 7. For example assume that we have a two-layer case as shown in Figure 8. The contribution from the upper layer is given by

$$\sigma_a = \sigma_1[1 - R_V(z)] \qquad (4a)$$

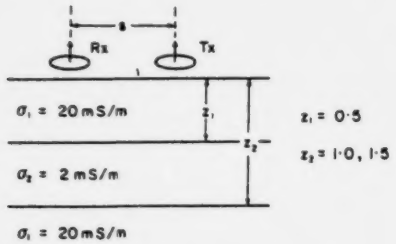
since all of the material below zero depth yields a relative contribution of unity or 100% to the meter reading. Conversely all of the material in the lower layer adds a contribution given by

$$\sigma_a = \sigma_2 R_V(z) \qquad (4b)$$

and the actual instrument reading will therefore be the sum of these two quantities

$$\sigma_a = \sigma_1[1 - R_V(z)] + \sigma_2 R_V(z) \qquad (5)$$

If the earth is three-layered as shown in Figure 9 the same procedure is employed to determine the instrumental response. In this example the calculations are performed for different middle layer thicknesses.



$$\sigma_a = \sigma_1[1-R(z_1)] + \sigma_2[R(z_1) - R(z_2)] + \sigma_3 R(z_2)$$

$z_2 = 1{\cdot}0$, $\sigma_a = 20[1-0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}44] + 20 \times 0{\cdot}44 = 15{\cdot}3$ mmho/m

$z_2 = 1{\cdot}5$, $\sigma_a = 20[1-0{\cdot}70] + 2[0{\cdot}70 - 0{\cdot}32] + 20 \times 0{\cdot}32 = 13{\cdot}2$ mmho/m

FIGURE 9. Calculation of response to three layer earth – center layer thickness varying.

The ease with which such calculations are performed facilitates survey preparation and interpretation. It is sometimes possible to make advance estimates of the electrical properties of the materials to be encountered during a survey or, alternatively, once on-site the operator can obtain the same information from sample measurements of the different materials. The procedures outlined above are then employed to estimate the apparent conductivity measured under various terrain conditions. Examples of such calculations for the EM31 are shown in Figure 10. As is seen in the appendix the algebraic expressions for $\phi(z)$ and $R(z)$ are very simple and are easily programmed on hand held calculators.

In Figure 10 the vertical dimensions are greatly exaggerated with respect to the horizontal dimensions. The question arises as to what degree of lateral uniformity is required before the earth can be considered as horizontally stratified or homogeneous. Survey experience indicates that if the ground conductivity does not significantly vary with horizontal distance within a radius of one intercoil spacing from the instrument the ground can be considered to be laterally uniform.

The above discussion referred to the use of vertical transmitter/receiver dipoles; it is equally possible to construct a cumulative response function for the horizontal coplanar dipole configuration and Figure 11 illustrates this function for both coil configurations. A comparison of the two curves illustrates that the vertical dipole mode of operation has approximately twice the effective exploration depth of the horizontal dipole mode.

IV. 3. Comparison with Conventional Resistivity Techniques

Many readers will be familiar with the two-layer curves employed to interpret data from conventional resistivity surveys using a Wenner array of four equally spaced electrodes. Using the techniques described in the previous section it is a simple matter to calculate two-layer curves for the electromagnetic technique; Figure 12 shows such curves for both the vertical and horizontal dipole configurations superimposed on standard Wenner curves. The general shape is similar but there are marked differences in detail. For vertical coplanar transmitter/receiver dipoles we see that when the substrate is the more resistive the response of the two systems is similar; however when the substrate is the more conductive the electromagnetic technique sees deeper in that the influence of the substrate, for a given conductivity contrast, is felt at smaller intercoil spacing than inter-electrode spacing. This is a general characteristic of electromagnetic systems which prefer to look through an insulator to a conductor rather than through a conductor to an insulator.

For the horizontal dipole configuration if the lower layer is the more resistive the effective exploration depth of the inductive technique is slightly less than the Wenner array; however, once again, in the case where the lower layer is the more conductive the exploration depth of the inductive technique is substantially greater.

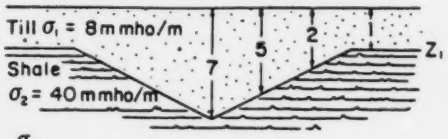
IV. 4. Resolution of Two-Layered Earth by Varying Intercoil Spacing

The principal advantage of the inductive electromagnetic technique over conventional resistivity lies in the speed and accuracy with which lateral changes of terrain conductivity can be measured. However this technique can also be used to measure the vertical variation of conductivity by expanding the intercoil spacing in a manner analogous to that in which the electrode spacing is expanded in conventional resistivity sounding techniques. The current state-of-the-art, however, is such that relatively few intercoil spacings can be employed; for example the EM34-3 can be operated with an intercoil spacing of 10, 20 or 40 meters. This feature is somewhat mitigated by the fact that the instruments can be used in either the vertical or horizontal dipole modes which, as shown in a previous section, exhibit different sensitivity to various depths thus yielding more information than would be available by simply using three spacings with one coil orientation.

To interpret a two-layef geometry the two-layer curves for both dipole configurations are superimposed on a common plot as shown

CROSS-SECTIONS

BURIED RIVER VALLEY

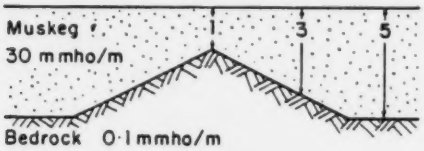


$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{40}{8} = 5$$

Z_1 (m)	σ_a (mmho/m)
1	32·6
2	26·9
5	18·6
7	16·0

BEDROCK HIGH

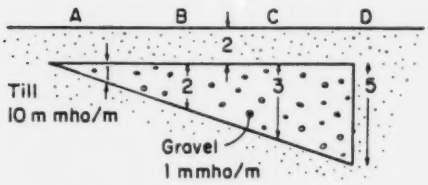


$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{0{\cdot}1}{30} = 0{\cdot}0033$$

Z_1 (m)	σ_a (mmho/m)
1	6·9
3	15·9
5	20·1

GRAVEL DEPOSIT



$$\frac{\sigma_a}{\sigma_1} = 1 - R(Z_1) + k_2[R(Z_1) - R(Z_2)] + k_3 R(Z_2)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{1}{10} = 0{\cdot}10$$

$$k_3 = \frac{\sigma_3}{\sigma_1} = 1{\cdot}00$$

station	σ_a (mmho/m)
A	8·9
B	8·2
C	7·7
D	6·9

FIGURE 10. EM31 calculated response across various geological features, using R (Z) corrected for instrument operation at waist (1 meter) height. Coil separation s = 3.67 meters.

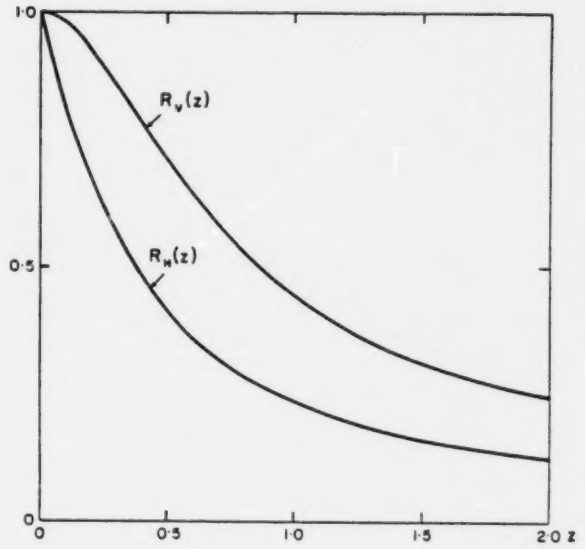


FIGURE 11. Cumulative response versus depth for vertical and horizontal dipoles.

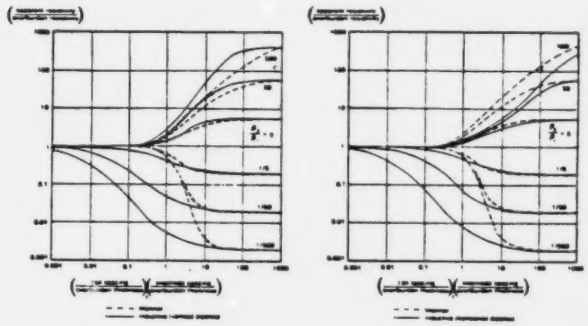


FIGURE 12. Comparison of Wenner array and inductive electromagnetic sounding curves for a two layer earth.

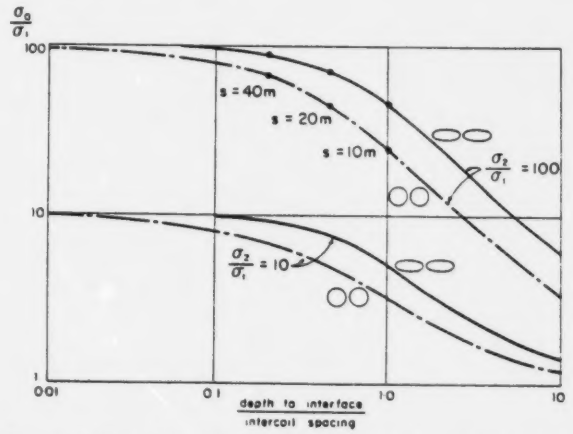


FIGURE 13. Two layer earth response curves (σ_2/σ_1 = 10,100; intercoil spacing varied). Dots indicate typical survey results.

in Figure 13. The six data points obtained by making measurements with two coil orientations and three intercoil spacings are plotted to the same scale on a piece of transparent paper and are translated vertically and horizontally on the two-layer curves to ascertain whether a satisfactory fit can be achieved. In the event that such a fit can be made, the earth does exhibit two-layer characteristics and the values of conductivity for both layers and the thickness of the upper layer are directly read off.

IV. 5. Resolution of Two-Layered Earth by Varying Instrument Height

In the case of the EM31 the intercoil spacing is rigidly fixed so that the technique described above is not available to analyse a layered earth. It is, however, possible to raise the instrument above the ground, measuring the apparent conductivity as a function of instrument height for both the vertical and horizontal dipole configurations. This has the effect of shifting the response curves of Figure 6 upwards through the various regions of the earth and the variation of apparent conductivity with height is therefore of diagnostic value in determining the nature of any layering. It is a straightforward matter to calculate the response of the instrument as a function of height for various two-layered earth geometries and typical curves are shown in Figure 14b. To use the curves one simply plots the measured apparent conductivity versus height for both coil configurations on a piece of transparent paper to the same scale as Figure 14b and shifts the plotted data vertically until good agreement is achieved with one of the curves, whereupon the two conductivities and the upper layer thickness are immediately determined as in the illustrated case history of Figure 14c.

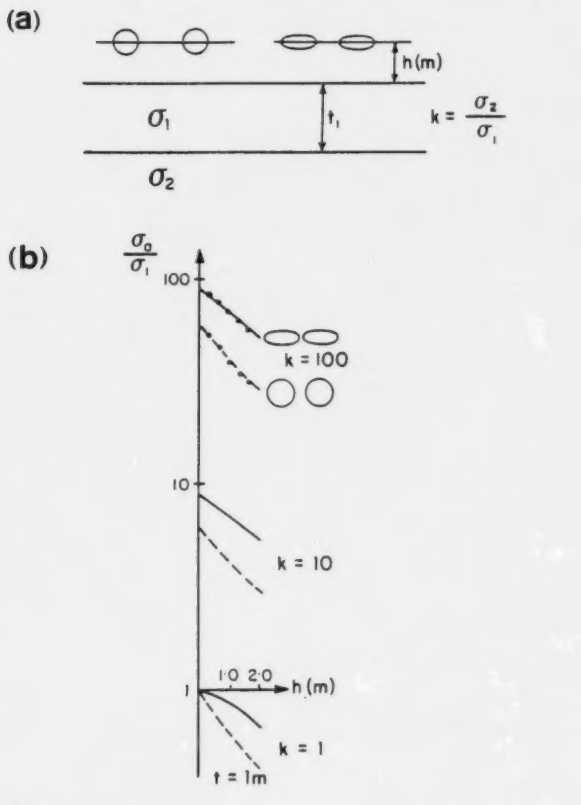


FIGURE 14. Two layer earth response curves (σ_2/σ_1 = 1, 10, 100; instrument height varied). Dots are actual survey results.

In the event that the conductivity of either one of the two layers is known to be much less than the other, so that its contribution to the meter reading is negligible, it is simply necessary to lay the instrument on the ground, take a reading, lay it on its side, take a second reading, and from these two values one can immediately calculate the conductivity of the more conductive layer and the thickness of the upper layer.

V. ADVANTAGES AND DISADVANTAGES OF INDUCTIVE TERRAIN CONDUCTIVITY MEASUREMENTS

V. 1. Advantages

The advantages of the use of inductive electromagnetic techniques to measure terrain conductivity are as follows:

(i) *Excellent resolution in conductivity.* It was stated in Section I that a problem with conventional resistivity was that the presence of localized resistivity inhomogeneities near the potential electrodes caused large errors. If we examine the current flow in a homogeneous halfspace for the inductive technique described herein we realize that in the vicinity of the transmitter the current density is very high and we might expect the presence of a conductive inhomogeneity located here to have a large effect. However where the current density is high, the radius of the current loops is small and their distance from the receiver coil large, so that these loops do not couple well magnetically with the receiver. The effect of changing this current by varying the local conductivity is consequently negligible. The lateral extent of the volume of earth whose conductivity is sensed by the inductive technique is approximately the same as the vertical depth. The result is that small changes in conductivity, for example of the order of 5% or 10%, are easily and accurately measured.

(ii) *No current injection problems.* Since currents are magnetically induced in the earth, current injection problems encountered with conventional resistivity in materials such as gravel, bedrock, permafrost, snow and ice, etc., are not encountered with this type of instrumentation.

(iii) *Simple multi-layered earth calculations.* This matter is dealt with at length in Section IV.

(iv) *Easy, rapid measurements.* A problem with the conventional Wenner array is that in order to survey to an effective depth a the array must be 3a in length and the total length of wire required 4a, used in four sections. This presents many opportunities for snagging and breaking the wire. Furthermore each measurement requires insertion of four electrodes and relatively careful measurement of the inter-electrode spacing. These features are avoided with the inductive electromagnetic techniques and it is no exaggeration to say that a survey can often be carried out five to ten times faster using this technique. Indeed with either the EM31 or the EM34-3 it is usually possible under average terrain conditions to survey 5 to 7 line-kilometers a day with a station spacing of 25 or 50 meters.

V. 2. Disadvantages

As with all geophysical instruments, there are some limitations and disadvantages to the use of inductive electromagnetic techniques and these are as follows:

(i) *Limited dynamic range (1 – 1000 mmhos per meter).* At low values of terrain conductivity it becomes difficult to magnetically induce sufficient current in the ground to produce a detectable magnetic field at the receiver coil. Conversely at high values of conductivity the quadrature component of the received magnetic field is no longer linearly proportional to terrain conductivity as is shown in the appendix.

(ii) *Setting and maintaining the instrument zero.* Ideally in order to set the zero the instrument would be suspended in free space

and the zero set there. The more acceptable alternative is to search out a region of very resistive ground, to accurately measure its conductivity using conventional techniques, and to set the instrumental zero at that location. This is the procedure which is actually followed.

It is necessary that this zero be accurately maintained over long periods of time and over the wide variations of temperature encountered during geophysical survey in various parts of the world. This produces tight constraints on the circuitry, with the result that the zero may be in error by up to ±0.2 mmhos per meter. Such an error would be negligible over the usual range of terrain conductivities; however in the event that measurements are being made on highly resistive ground the zero error can become significant.

(iii) *Limited Vertical Sounding Capability*. In theory it is possible to use a system such as the EM34-3 at a continuum of intercoil spacings to yield more information about electrical layering in the ground. To achieve a wide variety of inter-electrode spacings with conventional resistivity equipment is simple; in the case of the inductive electromagnetic technique the rapid fall-off of the magnetic field from the dipole transmitter introduces a serious dynamic range problem. In due course there will undoubtedly be instrumentation with a wider variety of spacings at the expense of additional complexity.

VI. CASE HISTORIES

This section describes several case histories obtained with the EM31 and the EM34. The surveys (i) illustrate the resolution in conductivity that can be achieved, (ii) compare the results obtained with conventional resistivity and (iii) illustrate the use of the latter for locating sand, gravel and conductive minerals, determining bedrock topography (including locating a buried river channel) and mapping the pollution plume from a land-fill site. In some cases the indicated conductivity has been converted to resistivity to facilitate comparison with conventional resistivity survey results.

Case History #1

Location: Mississauga, Ontario
Instrument: EM31
Application: Illustrates resolution and repeatability of EM31

For this case history a Rustrak chart recorder was used to monitor the output of an EM31. A line of length 200 meters was traversed in a field in both easterly and westerly directions. Figure 15 demonstrates that the instrument is resolving conductivity changes of less than 1 mmho/m (1% of full scale deflection) and that the repeatability is of the same order. In fact the repeatability is limited in this case by the resolving power of the chart recorder itself. It should furthermore be noted that the instrument is detecting spatial changes in conductivity of a few meters in length – compatible with the intercoil spacing of 3.7 meters.

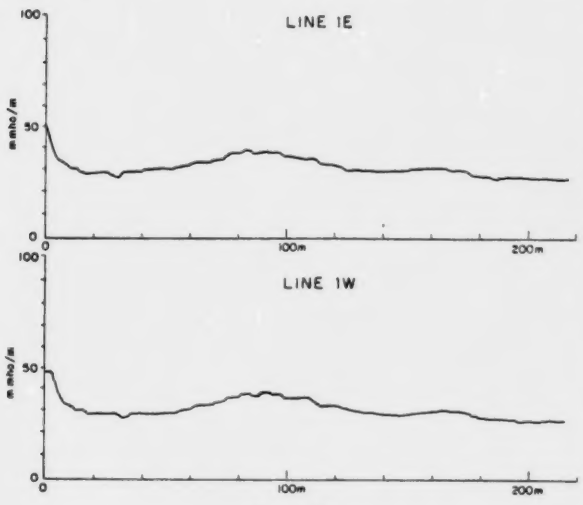


FIGURE 15.

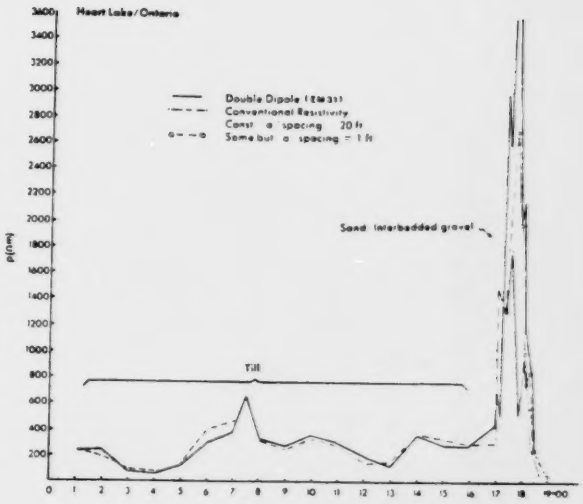


FIGURE 16. Test survey line – Heart Lake, Ont.

Case History #2

Location: Hearth Lake, Ontario
Instruments: EM31
Conventional resistivity apparatus
Application: Location of sand/gravel
Comparison of EM31 and conventional resistivity

In this survey a line 1900 ft. (580 meters) in length was surveyed with a measurement interval of 100 ft. (30 meters). The survey area was generally located on a buried esker, however the last few survey stations, 17 + 00 to 19 + 00, traversed a region of exposed sand and gravel (often occurring in the form of concretions) and over this portion of the line measurements were made every 10 ft. (3.0 meters).

The conventional resistivity profile was carried out using a Wenner array with an a spacing of 20 ft. (6.1 meters) except between stations 17 + 00 and 19 + 00 where the a spacing was reduced to 1 ft. (0.30 meters).

In general the correlation between the two sets of data is excellent, and demonstrates the ability of the EM31 to generate good quantitative data even in regions of low conductivity. Over the esker the EM31 was actually read continuously down the line – the data was recorded only at the 100 ft. intervals, with the exception of the reading at station 7 + 50 which was also recorded since it was noted that a conductivity low occurred there. Such an anomaly was, of course, missed by the conventional resistivity where measurements were only made every 100 ft.

Both sets of data become rather erratic between stations 17 + 00 and 19 + 00 as a result of the very rapid lateral changes in resistivity arising from the concreted material referred to above.

Case History #3

Location: Cavendish, Ontario.
Instrument: EM31
Application: Location of metallic type conductors

This survey line, of length 2000 ft. (610 meters), is located at a site

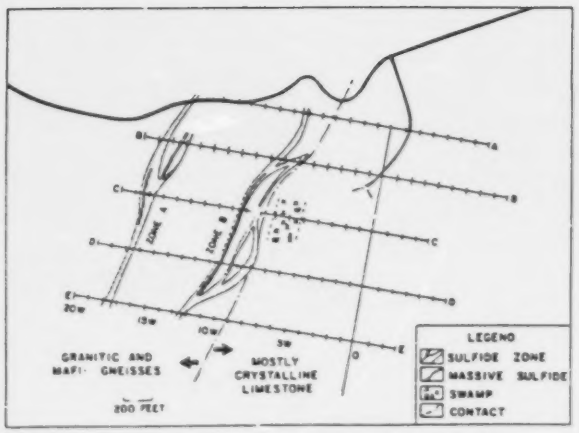


FIGURE 17. Geologic map of the Cavendish test site and the grid of traverse lines used in geophysical studies (after Ward et al [3]).

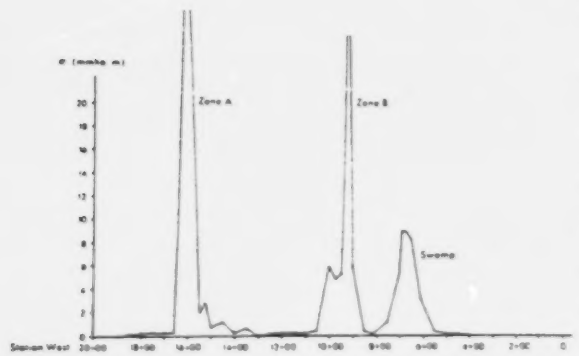


FIGURE 18. EM31 survey of Cavendish test range Line 'C'.

in Ontario which is often used by Canadian instrumentation manufacturers to test new electromagnetic geophysical equipment. The survey, along line C, illustrates response from both the swamp and the two zones of metallic mineralization. Although measurements were only taken every 50 ft. (15 meters) both zones are well delineated and when such high responses are encountered localization to within a few meters is quickly and easily carried out.

Inasmuch as the EM31 and EM34-3 were designed to map terrain conductivity at the conductivity levels encountered in typical soils both instruments are extremely sensitive electromagnetic detectors. For example on the most sensitive scale, full scale deflection for the EM31 is 800 ppm of the primary magnetic field and for the EM34-3 it is 3800 ppm. Such sensitivity makes either instrument useful for detecting metallic type conductors at what are very low conductivity levels by normal standards.

Case History #4

Location:	Mississauga, Ontario
Instruments:	EM31, EM34
Application:	Determination of bedrock topography

Total line length for this survey was 8400 ft. (2600 meters) and measurements were made every 100 ft. (30 meters) with both the EM31 and the EM34 – an earlier version of the EM34-3 which had two intercoil spacings vis. 100 ft. (30 meters) and 50 ft. (15 meters). The survey was performed to outline the cross-sectional profile of a

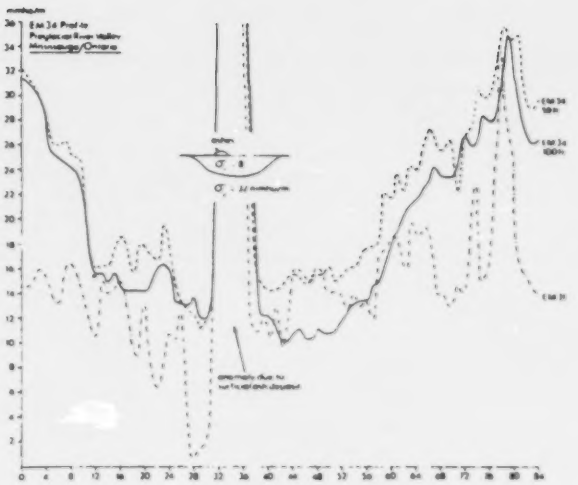


FIGURE 19. EM31 and EM34 survey line over preglacial river valley, Mississauga, Ontario.

buried preglacial river valley whose existence had been suggested from water-well data. At either intercoil spacing the time required for the EM34 profile was 1-1/2 hours, resulting in approximately one survey measurement per minute – including the time to walk the 100 feet between measurement stations. The time taken for the subsequent EM31 survey was similar.

Typical bedrock conductivity in the area is approximately 30 mmho/m, whereas an average value for the conductivity of the infilling glacial till is of the order of 8 to 12 mmho/m. Thus the EM34 at either intercoil spacing yields approximately 30 mmho/m at the valley edges where the overburden is thin and 12 to 14 mmho/m at the valley centre. The EM31 yields values of 14 to 18 mmho/m at the valley edges (slightly affected by the presence of bedrock) and approximately 10 mmho/m at the valley centre. The interpreted depth of the valley, based on the model shown in the figure, is approximately 120 feet (36 meters) which is in reasonable agreement with the water-well data value of 150 feet (45 meters), bearing in mind that the three sets of data show that a two-layer model is an over simplification.

The conductivity high which occurs between stations 32 and 38 results from a very large pile of waste furnace ash lying on the surface.

Case History #5

Location:	Camp Borden, Ontario
Instruments:	EM31, EM34
	Conventional resistivity apparatus
Application:	Mapping groundwater salinity
	Comparison of EM34 and conventional resistivity

Geophysical surveys were carried out over a sanitary landfill site using, in addition to other instruments, an EM31, EM34 and conventional resistivity [4]. The survey results in the accompanying figures illustrate the good agreement between these techniques and also indicate the reduction in survey time achieved using inductive electromagnetic techniques. Particularly interesting are the vertical variations in resistivity as shown by the EM31 at 3.7 m intercoil spacing and the EM34 at 15 and 30 m spacing.

VII. SUMMARY

This technical note describes in detail the principles of mapping the electrical conductivity of the ground using magnetically induced

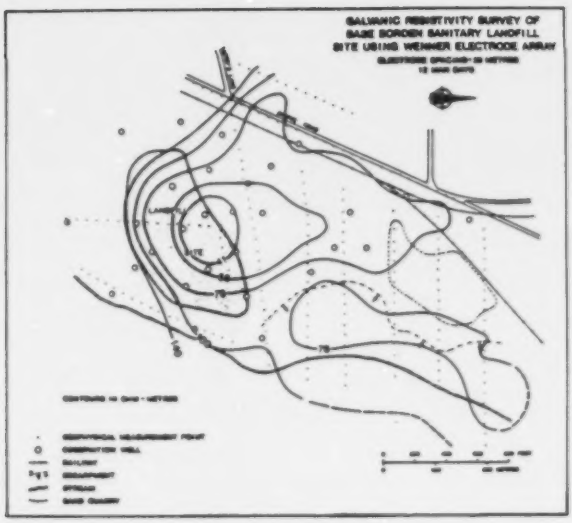


FIGURE 20(a).

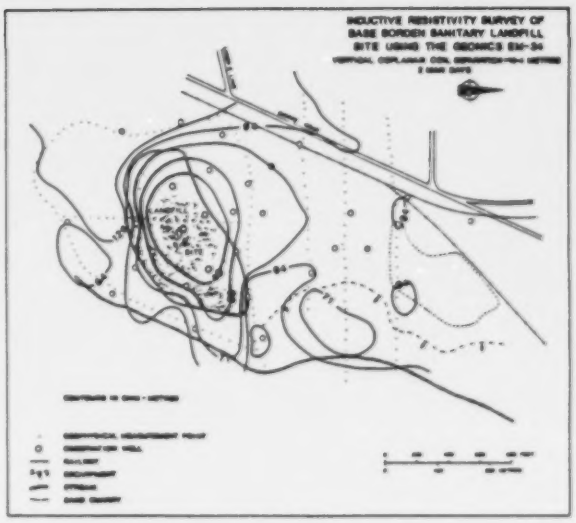


FIGURE 20(c).

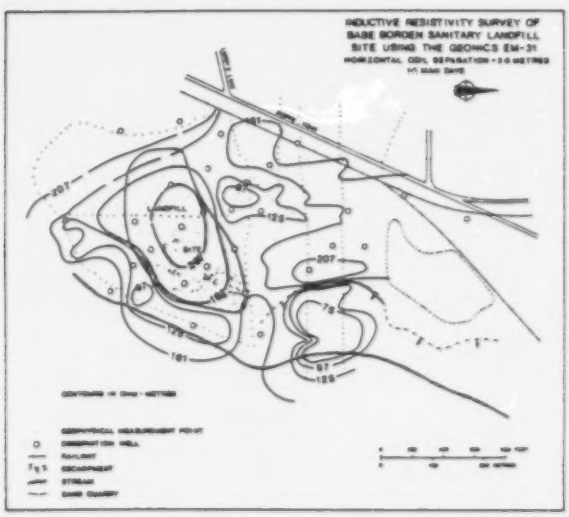


FIGURE 20(b).

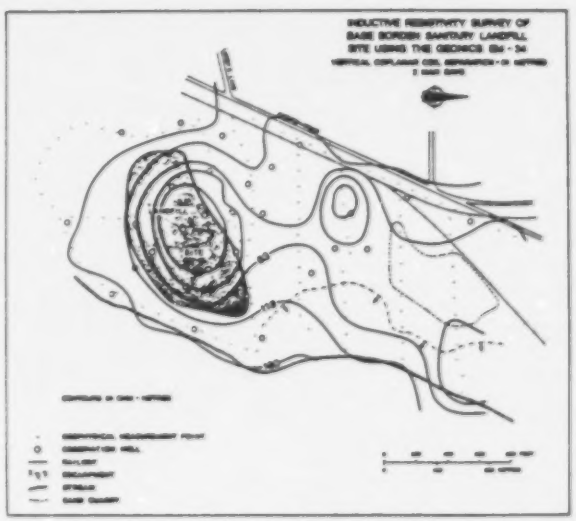


FIGURE 20(d).

currents at low frequencies. It has been shown that certain advantages can be derived from working at low values of induction number. Amongst these are excellent resolution in conductivity, a substantial reduction in man-hours necessary to carry out a conductivity survey and a simplification in the calculation of layered earth response.

Two points should be kept constantly in mind when performing surveys of this type to map geology. The first is that these instruments map only the electrical conductivity. If the conductivity does not vary significantly with the geological environment, or if parameters other than the geology also influence the conductivity, the survey results may be difficult to interpret.

The second point is that measurement of terrain conductivity, like any other geophysical measurement, must begin and end with geology. Such measurements are only an aid to help visualize geological conditions which cannot be seen. It is always necessary to interpret geophysical data against known geology from out-crops, boreholes, or any other such "bench marks". Geophysical measurements can be very effective by allowing interpolation between such sources, or extrapolation away from them. However in every case knowledge derived from geophysical measurements must be eventually reconfirmed against known geological conditions.

BIBLIOGRAPHY

(1) Keller, G.V., Frischknecht, F.C. Electrical Methods in Geophysical Prospecting. Pergamon Press 1966.

(2) Wait, J.R. 1962. A Note on the Electromagnetic Response of a Stratified Earth. Geophysics V.27, pp 382-85.

(3) Ward, S.H., Pridmore, D.F., Rijol, Glenn W.E. Multispectral Electromagnetic Exploration for Sulphides. Geophysics Vol. 39 No. 5 p. 666. 1974.

(4) Survey carried out by Dr. J. Greenhouse, University of Waterloo, Waterloo, Ontario.

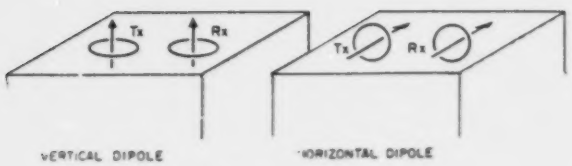


FIGURE AI. Vertical and horizontal dipole coil configurations.

APPENDIX: Theory of Operation at Low Induction Numbers

Consider the two coil configurations shown in Figure AI. In each case the transmitter coil is energized with alternating current at a frequency f Hertz. The measured quantity is the ratio of the secondary magnetic field H_s at the receiver when both coils are lying on the surface of the homogeneous half-space of conductivity σ to the primary magnetic field H_p in the absence of the half-space (i.e. as if the coils were in free space). The spacing between the coils is s meters.

The field ratios for vertical and horizontal dipole configurations are given by equations (1) and (2) respectively.

$$\left(\frac{H_s}{H_p}\right)_v = \frac{2}{(\gamma s)^2}\{9 - [9 + 9\gamma s + 4(\gamma s)^2 + (\gamma s)^3]e^{-\gamma s}\} \quad (1)$$

$$\left(\frac{H_s}{H_p}\right)_H = 2\left[1 - \frac{3}{(\gamma s)^2} + [3 + 3\gamma s + (\gamma s)^2]\frac{e^{-\gamma s}}{(\gamma s)^2}\right] \quad (2)$$

where $\gamma = \sqrt{i\omega\mu_o\sigma}$

$\omega = 2\pi f$

f = frequency (Hz)

μ_o = permeability of free space

$i = \sqrt{-1}$.

These expressions are complicated functions of the variable γs which is in turn a reasonably complicated (complex) function of frequency and conductivity. However, as will be shown below, under certain conditions they can be greatly simplified.

A well known characteristic of a homogeneous half-space is the electrical skin depth δ, which is defined as the distance in the half-space that a propagating plane wave has travelled when its amplitude has been attenuated to 1/e of the amplitude at the surface. The skin depth is given by

$$\delta = \sqrt{\frac{2}{\omega\mu_o\sigma}} = \frac{\sqrt{2i}}{\gamma} \quad (3)$$

and therefore

$$\gamma s = \sqrt{2i}\,\frac{s}{\delta} \quad (4)$$

The ratio s/δ, the intercoil spacing divided by the skin depth, is defined as the induction number B, whereupon

$$\gamma s = \sqrt{2i}\,B \quad (5)$$

Now if B is much less than unity (ie $\gamma s \ll 1$) it is a simple matter to show that the field ratios of equations (1) and (2) reduce to the simple expression

$$\left(\frac{H_s}{H_p}\right)_v \simeq \left(\frac{H_s}{H_p}\right)_H \simeq \frac{iB^2}{2} = \frac{i\omega\mu_o\sigma s^2}{4} \quad (6)$$

which is the equation given in Section II.

The magnitude of the secondary magnetic field is now directly proportional to the ground conductivity and the phase of the secondary magnetic field leads the primary magnetic field by 90°.

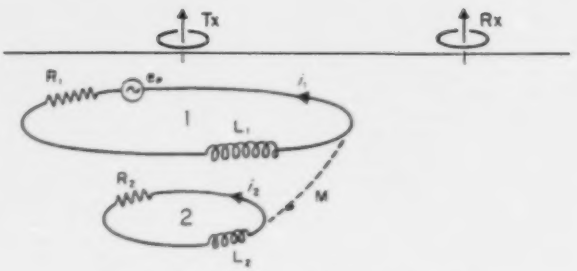


FIGURE AII. Electrical model for vertical dipoles.

To make B much less than unity we see that we must make s very much less than δ and thus

$$\omega \ll \frac{2}{\mu_o\sigma s^2} \quad (7)$$

That is, having decided on a value for s (which fixes the effective depth of penetration under the condition $B \ll 1$), the maximum probable ground conductivity is estimated and the operating frequency is chosen so that equation (7) is always satisfied.

The apparent conductivity which the instrument reads is then defined by

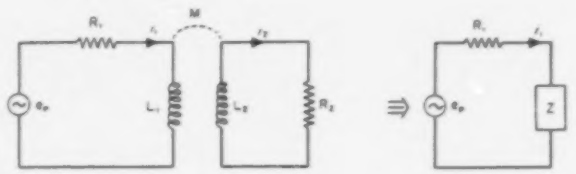
$$\sigma_a = \frac{4}{\omega\mu_o s^2}\left(\frac{H_s}{H_p}\right)_{\substack{\text{quadrature}\\ \text{component}}} \quad (8)$$

To examine the reasons for this simplification let us focus our attention on the vertical dipole coil configuration shown in Figure AII since symmetry makes this configuration the simplest to understand.

Consider current loop 1. The primary emf e_p causing this current to flow is given (through Faraday's law) by the time rate of change of the primary magnetic flux from the transmitter through this loop. Three impedances cause the current to be limited. These arise from (i) the electrical resistance R_1 of the loop, (ii) the fact that the current i_1 generates its own magnetic field which causes a time-varying secondary magnetic flux through the loop (self-inductance, L_1), and (iii) the fact that all other current loops such as i_2 generate their own magnetic fields which in turn cause a time-varying magnetic flux to link with loop 1 (mutual-inductance, M).

The equivalent circuit for this configuration is easily derived from elementary circuit theory with the result shown in Figure AIII.

The complex impedance Z incorporates all of the affects of magnetic coupling between current loop 1 and any other current loop 2. We see from this expression that Z can be made arbitrarily small by reducing $\omega = 2\pi f$, the operating frequency. When Z is thus



$$Z = i\omega L_1 + \frac{\omega^2 M^2}{R_2 + i\omega L_2}$$

$$i_1 = \frac{e_p}{R_1 + Z}$$

FIGURE AIII. Equivalent circuit for model of Figure AII.

made much smaller than R_1 the current flow in loop 1 is simply given by

$$i_1 = \frac{e_p}{R_1} = \frac{i\omega\phi_p}{R_1} = i\omega\phi_p G_1 \qquad (9)$$

where ϕ_p = primary flux linking loop 1
G_1 = conductance of loop 1 ($G_1 = 1/R_1$)
$i = \sqrt{-1}$

We see that the magnitude of the current is linearly proportional to the loop conductance and furthermore that the phase of the current leads the primary flux by 90°. Since the secondary magnetic field at the receiver from current i_1 is in phase with and directly proportional to i_1 it too will be directly proportional to G and will lead the primary flux by 90°. Thus

$$\left(\frac{H_s}{H_p}\right) \propto i\omega G_1 \qquad (10)$$

which has the same dependence on frequency and conductance as equation (6). We infer therefore, that the condition $B \ll 1$ is equivalent to stating that for all current loops that affect the receiver output the operating frequency is so low that we can ignore any magnetic coupling between the loops. Thus the current that flows in any loop is (i) completely independent of the current that flows in any other loop since they are not magnetically coupled and (ii) is only a function of the primary magnetic flux linking that loop and of the local ground conductivity.

The lack of interaction between current loops is of great importance in simplifying the data reduction procedures. Of equally great significance is the fact that for any value of B and for any orientation of a magnetic dipole (or indeed of any magnetic source) over either a uniform halfspace or a horizontally stratified earth it can be shown that all current flow is horizontal. That this is the case for a vertical dipole is easy to see from symmetry; for a horizontal dipole it is less evident but equally true. Thus, in a horizontally layered earth no current crosses an interface which is fortunate since, if it did, changing either of the conductivities would, by virtue of refraction of the current, change the direction of the current as it flowed from one medium to the other.

If no current flow crosses an interface and if there is no magnetic coupling between current loops, changing the conductivity of any one of the layers of a horizontally stratified earth will not alter the geometry of the current flow. Varying the conductivity of any layer will proportionately vary only the magnitude of the current in that layer. To calculate the resultant magnetic field at the surface of a horizontally layered earth it is simply necessary to calculate the independent contribution from each layer, which is a function of its depth and conductivity, and to sum all the contributions.

The functions $\phi(z)$ and $R(z)$ discussed in Section II define the relative influence of current flow as a function of depth. Their derivation is involved and will not be given here. The resultant expressions are, however, simple and easily programmed into hand calculators:

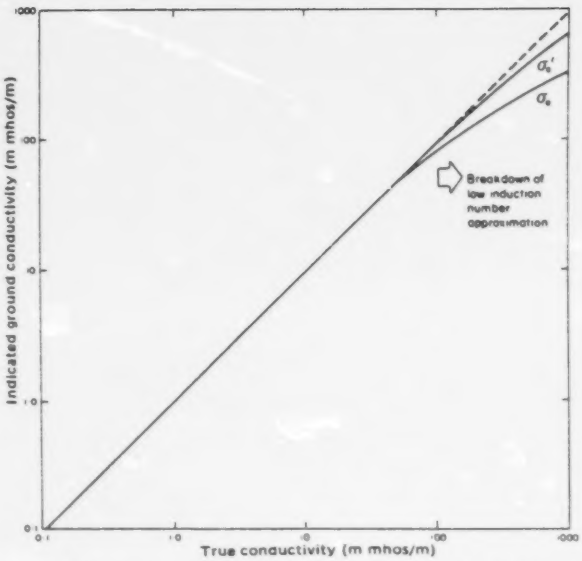


FIGURE AIV. Plot of indicated conductivity for EM31 versus true (homogeneous half-space) conductivity for both vertical (σ_a) and horizontal (σ_a') dipoles.

$$\phi_V(z) = \frac{4z}{(4z^2 + 1)^{3/2}} \qquad (11)$$

$$\phi_H(z) = 2 - \frac{4z}{(4z^2 + 1)^{1/2}} \qquad (12)$$

$$R_V(z) = \frac{1}{(4z^2 + 1)^{1/2}} \qquad (13)$$

$$R_H(z) = (4z^2 + 1)^{1/2} - 2z \qquad (14)$$

where z is the depth divided by the intercoil spacing.

Finally it should be noted that for a given frequency and intercoil spacing as the terrain conductivity increases the approximation of equation (6) eventually breaks down and the instrumental output is no longer proportional to terrain conductivity. This effect is illustrated in Figure AIV, which plots apparent (indicated) conductivity against true (homogeneous halfspace) conductivity for both vertical and horizontal transmitter/receiver dipoles for the operating parameters of the EM31. As would be expected the horizontal dipoles exhibit linearity to greater values of conductivity as a result of the reduced depth of penetration in this configuration.

APPENDIX C

Operating Instructions For The EM 31 & EM 34-3

NOTE TO EM31 AND EM34 USERS:

One of the most common problems with the instrument is the contamination of battery contacts. To clean these contacts use fine sand paper (#400 or higher) and wipe several times over the contacts.

Ensure that the spring action of the battery holders is maintained. Bend holder sides slightly if necessary.

July 1985.

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OPERATING MANUAL

for

EM31-D

NON-CONTACTING

TERRAIN CONDUCTIVITY METER

Revised June 1984.

EM31 MANUAL

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EM31-D SPECIFICATIONS

Measured Quantities	(1)	Apparent conductivity of the ground in millimhos per meter
	(2)	Inphase component of the induced magnetic field
Primary Field Source		Self-contained dipole transmitter
Sensor		Self-contained dipole receiver
Intercoil Spacing		3.66 meters
Operating Frequency		9.8 kHz
Power Supply		8 disposable alkaline 'C' cells (approx. 20 hrs life continuous use)
Conductivity Ranges		3, 10, 30, 100, 300, 1000 mmhos/meter
Measurement Precision		± 2% of full scale
Measurement Accuracy		± 5% at 20 millimhos per meter
Noise Level		<0.1 millimhos per meter
Operator Controls		•Mode Switch •Conductivity Range Switch •Phasing Potentiometer •Coarse Inphase Compensation •Fine Inphase Compensation
Analog Output		Connector on EM31-D for dual channel analog recording of ground conductivity and inphase component
Dimensions		Boom : 4.0 meters extended 1.4 meters stored Console : 24 x 20 x 18 cm Shipping Crate: 155 x 42 x 28 cm
Weight		Instrument Weight: 9 kgm Shipping Weight: 23 kgm

EM31 MANUAL

1. INTRODUCTION

Measurement of ground resistivity is one of the oldest geophysical techniques. Table 1, taken directly from Heiland*, lists typical values of resistivity for a variety of geological materials (pages 4-7). The values given are in ohm-centimeters and must be divided by one hundred to give ohm-meters.

It will be observed that in most cases the actual resistivity itself is not diagnostic and a knowledge of the way in which the resistivity varies laterally and with depth is of great importance, since this permits us to "see" features as a result of their shape rather than their actual resistivity values. There is thus a requirement for instrumentation which permits the rapid and accurate measurement of terrain resistivity. Since the EM31 does not require electrical contact with the ground it fulfills this objective.

The basic principle of operation of the EM31 is simple. With reference to Fig. 1 a transmitter coil located at one end of the instrument induces circular eddy current loops in the earth. Under certain conditions fulfilled in the design of the EM31 the magnitude of any one of these current loops is directly proportional to the terrain conductivity in the vicinity of that loop. Each one of the current loops generates a magnetic field which is proportional to the value of the current flowing within that loop. A part of the magnetic field from each loop is intercepted by the receiver coil and results

* Heiland, C.A. Geophysical Exploration. Hafner Publishing Co., New York 1968

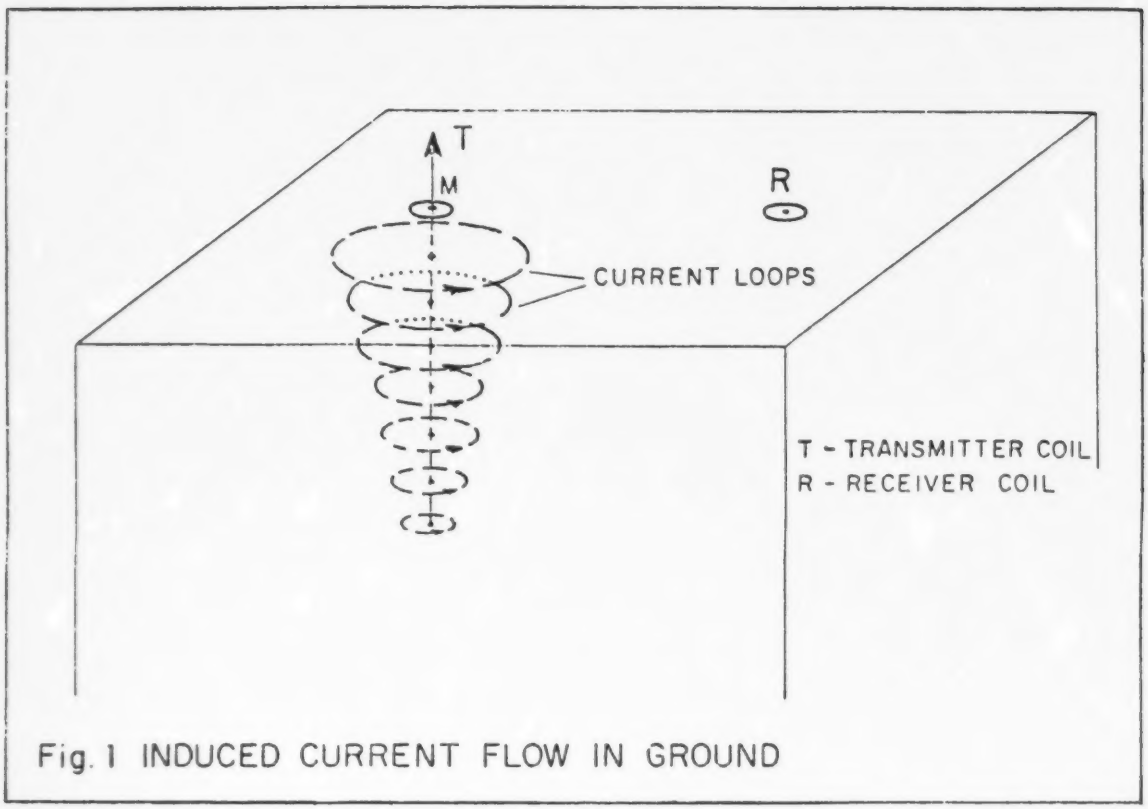


Fig. 1 INDUCED CURRENT FLOW IN GROUND

1. INTRODUCTION (cont'd)

in an output voltage which is therefore also linearly related to the terrain conductivity.

This instrument is calibrated to read the correct conductivity when the earth is uniform. In the event that the earth is layered, with each layer of different conductivity, the instrument will read an intermediate value as discussed in more detail in Section 5.2.

The unit of conductivity used is the millimho per meter. To obtain resistivity in ohm-meters the instrument reading is divided into 1000 - i.e., a reading of four millimhos per meter divided into 1000 gives two hundred and fifty ohm-meters.

Theoretical calculations show, as will be quickly evident to the operator, that the reading obtained is essentially independent of the orientation of the instrument with respect to the earth. There is, however, a small dependence on the height above the ground; lifting the instrument from the surface of a uniform earth to the normal operating height of about one meter results in a reduction in the reading of 12%. The calibration has been adjusted at the factory so that the instrument reads correctly over a uniform half-space when worn as shown in the data sheet. If the earth is layered, raising the instrument from the surface of the earth to the normal operating position can result in a reading which stays constant or even increases slightly with height. In general, readings made with the instrument at hip height will be sufficiently accurate, but for maximum accuracy the instrument can be laid on the ground as discussed in Section 5.2.

There are two components of the induced magnetic field measured by the EM31. The first is the quadrature-phase component which gives the ground conductivity measurement as described. The second is the inphase component used primarly in the EM31 for calibration purposes. The inphase component however is significantly more sensitive to large metallic objects and hence very useful when looking for buried metal drums. Although this component has been available in the standard EM31 by operating in the compensation mode (Section 2.2), both components are now available in the EM31-D from an analog output connector when coupled to a dual channel recorder.

TABLE 1A

RESISTIVITIES OF IGNEOUS & METAMORPHIC ROCKS

Rock	Locality	Investigator	Dia.	Freq.	Resistivity in ohm-cm							
					Intermediate Conductors							
					½	¼	⅛	1/16	1/32	1/64	1/128	1/256
Specimens												
Diabase	Idaho	Sundberg	3				3.1					
Granite	Bavaria	Hunkel	3							1		
Devonian slate	Harz	Ebert					2					
" "	"	"						6.5				
Porphyry, schistose	S. Australia	Edge & Laby		100			3					
Serpentine		Eve & Keys					3-	-2				
Diorite	Bavaria	Hunkel	3					1				
Gabbro	Mineville	Lee & Boyer		D.C.					1.0	—	1.4	
Garnet gneiss	Bavaria	Hunkel	3						2			
Hornblende gneiss	Mineville	Lee		D.C.						1-6		
Gray biotite gneiss	"	Lee & Boyer		D.C.						4		
Syenite	Bavaria	Hunkel	3							1		
In Situ												
Graphitic schist	Normandy	Schlumberger		16	1-	1						
Schists	Missouri	Poldini			2-	6						
Hard calc. schist	Belgian Congo	Geoffroy & Charrin				2-	1.1					
Mica schist (hard packed)	Washington, D. C.	Gish & Rooney		16			1.3					
Quartz porphyry (slightly altered)	Newfoundland	Kihlstedt				3.4						
Keweenawan lavas	Michigan	Hotchkiss, et. al.		10-15		1.2	—	4.4				
Greenstone	"	Rooney		16			1.1					
Porous trap-rock	"	"		16		1.6						
Pre-Cambrian Granite	Sweden	Sundberg					3-6					
	Washington, D. C.	Gish & Rooney		16			5					
Slightly altered syenite	Ontario	Kihlstedt		200			2.4					
							3.7					
Massive vein quartz	"	"		200					2			
Diabase	Michigan	Rooney		16		4.5						
Serpentine	Ontario	Kihlstedt		200		2.1						
						5.3						

TABLE 1B

RESISTIVITIES OF CONSOLIDATED SEDIMENTS[14]

Rock	Locality	Investigator	Dir.	Freq.	n°	Resistivity in ohm-cm 10^1	10^2	10^3	10^4	10^5	10^6
Shales and Slates											
Chattanooga shale (Dev.)	Cent. & south Illinois	Hubbert		50			2		1.4		
Shale & glacial drift	"	"		50			5				
Nonesuch shale	Houghton Co., Mich.	Hotchkiss, *et. al.*		10-15				1.8			
Shale	W. Hancock, Mich.	Rooney		60					2		
Slate		Lee, Joyce, & Boyer		0				6.4			
Clay (wet)	Jugoslavia	Lochnberg & Stern		D.C.			2.1				
Grinneld argillite	N½ sec. 23, T32N R20W, Flathead Co., Montana	Erdmann	dip 32°	16							
					10			1.7			
			∥ to strati-fication		20		9.6				
					20			1.1			
					30			1.0			
			⊥ to strike		10		8.7				
					20		7.4				
					40			1.1			
Grinneld argillite	" (Water's Edge)	"	dip 32°	16				1.3			
			∥ to strike		15			1.4			
					30			8.0			
								8.2			
					10			7.7			
Argillite (Missoula group); pre-Cambrian, thin-bedded, platy argillite; resembles Grinneld	Sec. 27, T 32N R20W, Flathead Co., Montana	"	dip 31°	16							
					10			1.4			
					20			1.6			
			⊥ to strike		30			1.5			
					40			1.4			
					50			1.5			
									1.1		
Conglomerates											
Great conglomerate outcrop	Eagle Harbor, Mich.	Hotchkiss, *et. al.*		10-15							
Calumet & Hecla conglomerates	Michigan	Rooney		60					2	1.3	
Sandstone											
Eastern sandstone	Michigan	Hotchkiss, *et al.*		10-15				3.5	1.2		
Eastern sandstone	"	Rooney		16				4.3			
Muschelkalk ss. (Triassic)	Lorraine	Schlumberger		16				7			
Sandstone (Tertiary Oligocene); soft, friable; extremely fine grained ss.; pale green to yellowish and buff; contains thin beds of lignite	Coal Creek Road, Flat head Co., Montana	Erdmann	dip = almost 0	16	10			8.8			
								9.8			
					20			6.2			
								6.7			
					30			4.8			

TABLE 1B cont'd

RESISTIVITIES OF CONSOLIDATED SEDIMENTS

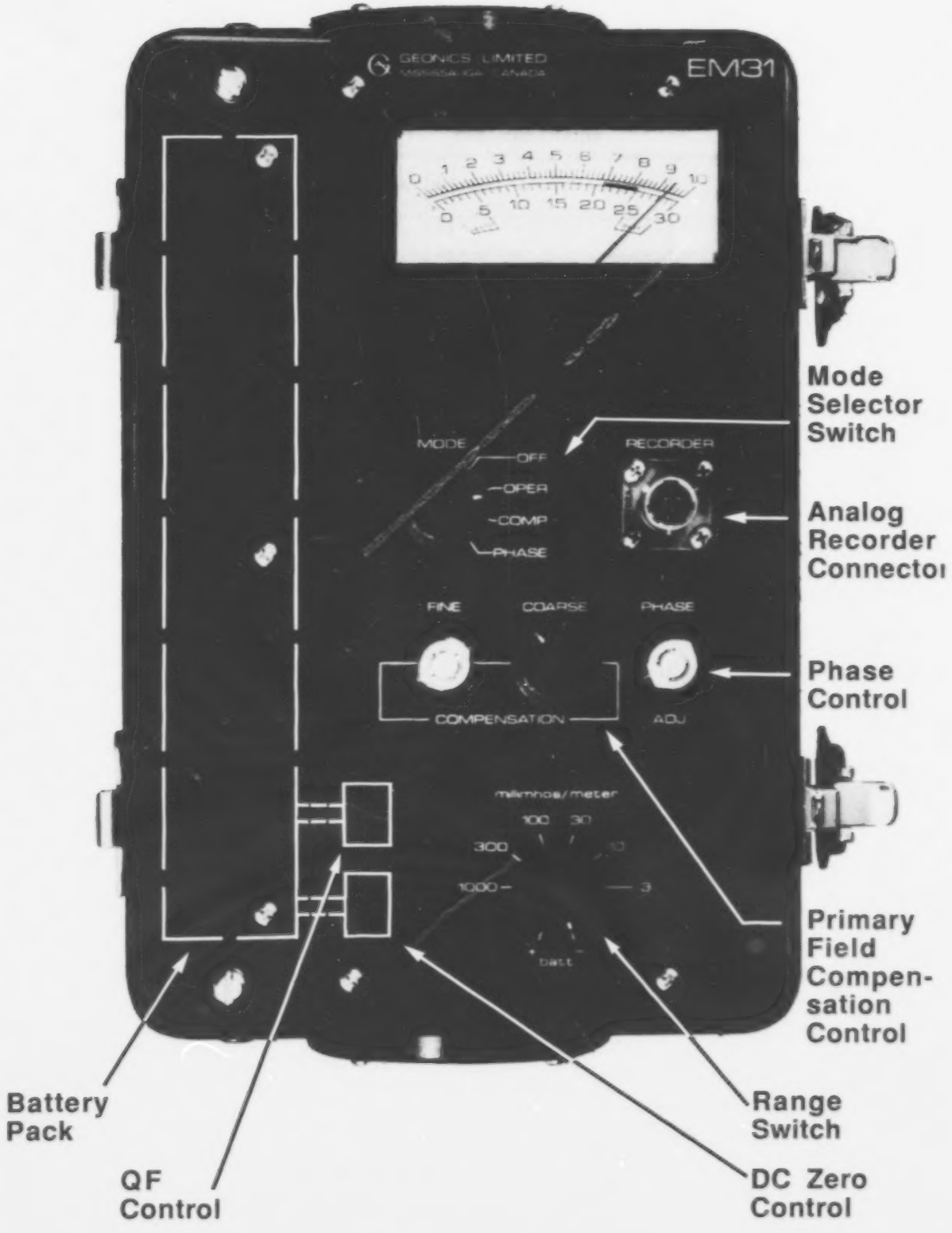
Rock	Locality	Investigator	Dir.	Freq.	ϕ°	Resistivity in ohm-cm					
						10^0	10^1	10^2	10^3	10^4	10^5
Armorican ss. compact Siliceous-Ordovician	Normandy	Schlumberger						1			
Ferruginous sandstone (Jurassic)	Switzerland	Koenigsberger						4			
Limestone											
Muschelkalk ls. (Triassic)	Lorraine	Schlumberger		16		6					
Limestone with lenses of hematite	Algeria	"					1.2-4				
Muschelkalk oolitic ls. (Triassic)	Lorraine	"		16			1.8				
Limestone	Mississippian (Missouri)	Poldini					3-4				
Siyeh ls., hard homogeneous, dark bluish-gray, siliceous magnesium ls.; pre-Camb.	SW cor. sec. 5 T29N R18W Flathead Co., Montana	Erdmann	dip 54°	16							
			∥ to strike		10		6.8	1.4			
					20			1.5			
					30			1.4			
			⊥ to strike		10		3.6				
					20		5.4				
							7.9				
					30		6.6				
							6.9				
					50		6.1				
							8.1				

TABLE 1C

RESISTIVITIES OF UNCONSOLIDATED FORMATIONS (MOSTLY QUARTERNARY)

Formation	Locality	Investigator	a[a]	Pass.	Resistivity in ohm-cm					
					10^1	10^2	10^3	10^4	10^5	10^6
Marls										
Marl & gypsum	Germany	Schlumberger		16	3–	1.2				
Marl & gypsum	Algeria	"		16		1-3				
Jarnisy marls	Lorraine	"		16		5				
Marls	"	Geoffroy				7				
Clay										
Clays with Mg salts	Australia	Rooney		16	1-2					
Clay (wet)	Palestine	Lochnberg		D.C.	5–	–4				
Boulder clay (no gravel)	Montana	Erdmann	10			2.1				
			20			2.3				
Marine clay	Ontario	Hawkins				3.6				
Dry clay	New Jersey	Feldman		40 me.[b]		5.1				
Wet clay	" "	"				8				
Boulder clay (wet)	Montana	Erdmann	20				1.1			
Alluvium and Silt										
Alluvium (moist)	Montana	"	10			2.3				
Silt (dry)	"	"	5			2.0				
			10			1.3				
			20			1.4				
Glacial out-wash (dry)	Washington (state)	"	10				1.3			
" "	"	"	10				1.6			
" "	"	"	10				2.1			
Fluvio glacial till (wet)	"	"	20				8.4			
			40				5.7			
			60				4.9			
			100				3.9			
Glacial	Connecticut	Leonardon					5			
River gravel (wet)	Montana	Erdmann	10				1.2			
" " "	"	"	10				1.4			
Yellow river sand (3.3% moisture)		Sundberg					1.7			
Yellow river sand (0.86% moisture)		"					8.3			
Stream gravel (wet)	Montana	Erdmann	10				3.3			
			15				3.3			
			20				3.2			
River gravel (wet)	Colorado	"	10				4.8			
			10				6.5			
			10				4.8			
							8.9			

[b] me. = megacycles = 10^6 cycles.


GEONICS LIMITED
EM31
MODE
OFF
OPER
COMP
PHASE
RECORDER
FINE
COARSE
PHASE
COMPENSATION
ADJ
millimhos/meter
100
30
300
10
1000
3
batt
Mode Selector Switch
Analog Recorder Connector
Phase Control
Primary Field Compen-sation Control
Range Switch
DC Zero Control
QF Control
Battery Pack

2. OPERATING INSTRUCTIONS

The EM31 can be used both to measure the electrical conductivity of the ground and to detect buried metal objects. Section 2.1 describes the procedure for measuring ground conductivity and section 2.2 for buried metal detection.

2.1 Ground Conductivity Measurements

2.1.1 Initial Set-up Procedure

a) Using the identifying labels on the tubes select the transmitter coil tube, align it with respect to the main tube, insert it and fix it with the clamp.

b) Check the battery condition, plus and minus, by setting the Mode switch (MODE SELECTOR SWITCH) to the OPER position and the Range switch to the +B and -B positions respectively. If the needle reads inside the BATT mark on the meter, batteries are in good condition, otherwise replace the batteries with a fresh set of C size alkaline batteries.

c) Check the zero reading by setting the Mode switch to the OPER position and the Range switch to the least sensitive position 1,000 mmhos/meter (this minimizes any external noise interference while checking the zero position). If a zero adjustment is required adjust the DC ZERO CONTROL located under the front panel to obtain a zero reading. To do this the battery pack must be removed to gain access to the controls.

d) Align and connect the receiver coil tube to the main frame tube. The instrument is now ready to proceed with the functional checks.

2.1.2 Equipment Functional Checks

The Range switch should be set at 30 millimhos/meter position for all the following tests. (If the reading is off scale, i.e., greater than 30 millimhos/meter, see note.)

a) Set the Mode switch to the COMP position and adjust the meter reading to zero using the COARSE and FINE COMPENSATION controls.

b) To check the phasing of the instrument set the Mode switch to the PHASE position. Note the meter reading and rotate the COARSE control one step clockwise. If the meter reading remained the same, the phasing is already correct; return the COARSE control to its original position (one step counter clockwise) and no further adjustment is necessary.

If there was a difference in the meter readings taken before and after the COARSE control was rotated one step clockwise then a phase adjustment is required. With the COARSE control in its original position adjust the PHASE potentiometer about 1/4 turn clockwise and note the new meter reading. Rotate the COARSE control one step clockwise, take a reading, and return the COARSE control to its original position. If the difference in meter readings has decreased, repeat the procedure using a further clockwise adjustment, until rotating the COARSE control the one step clockwise produces no change in the meter reading.

If, on the other hand, the difference in meter readings was increased, the PHASE potentiometer should be rotated in a counter clockwise direction instead and the procedure described above repeated until there is no change in the meter readings. Always remember to set the COARSE control back to its original position. This can be confirmed by setting the Mode switch in the COMP position and checking that the meter reads zero. If it does not read zero, repeat steps (a) and (b).

c) To check the sensitivity of the instrument, set the Mode switch to the COMP position and rotate the COARSE control clockwise one step. The meter should read between 75% and 85% (22 to 26 millimhos/meter) of full scale deflection (inside black mark). It is unlikely that the sensitivity of the instrument will vary, however it may be useful to record the actual meter reading for comparison at a later date.

Return the COARSE switch to its original position and the EM31 is now ready to make ground conductivity measurements.

NOTE: When conducting the functional tests over ground of higher conductivity than 30 millimhos/meter, the Range switch should be set at the appropriate level. At whatever level the Range switch is in, the reading taken in (c) should still be between 22 and 26 millimhos/meter.

2.1.3 Operating Procedure

a) Wearing the instrument with the shoulder strap adjusted so that the instrument rests comfortably on the hip as shown, switch the Mode switch to the OPER position and rotate the Range switch so that the meter reads in the upper two thirds of the scale. The full scale deflection is now indicated by the Range switch and the instrument is reading the terrain conductivity directly in millimhos per meter.

b) The EM31 can be operated continuously while moving from one measurement station to the next however, the instrument has a time constant of about one second for which the operator should adjust his walking speed to obtain greatest accuracy.

Alternatively, to extend battery life the instrument can be switched on at each measurement station when not using a recorder. The operator will notice that the type of integrator used results in a slight initial overshoot of the needle at turn on. This is normal, and that at least two seconds should be allowed after turn on before the measurement is taken.

2.2 Buried Metal Detection

2.2.1 Set-up and Operating Procedure

The inphase component of the magnetic field is significantly more sensitive to large metallic objects than the quadrature-phase component used for ground conductivity measurements.

a) The inphase component is readily measured with the EM31 by simply taking the reading with the Mode switch in the COMP position rather than in the OPER position.

It is recommended that the 30 mmho/m range be used since it usually gives adequate sensitivity, however more or less sensitive positions of the Range switch may also be used.

b) To carry out a survey measuring the inphase component set the Mode switch to the COMP position and adjust the COARSE and FINE compensation controls so that a meter deflection of about 20% of full scale deflection is obtained. (The procedure of adjusting to 20% of the full scale deflection rather than to zero is only a convenience to allow for negative readings on the meter and under certain conditions a possible change in the reference level. For example, a sudden jar to the instrument can result in a small positive or negative change in the inphase reference level).

The survey is then carried out exactly as if the conductivity were being measured.

c) This lack of a true zero reference should not cause any serious problems since when using the inphase component one is usually only looking for buried metallic objects.

These will be easily recognizable by relatively localized meter deflections occuring either singly or in a series of responses depending on the number of buried objects, their spacing and depth of burial.

(1): The 20% offset should only be used when the inphase component only is being measured continuously. If both conductivity (quadrature phase) and inphase measurements are being made at each station the procedure described in 2.1.2 (a) should be used so that accurate ground conductivity measurements are obtained. If negative inphase measurements are obtained one should check the inphase reference level and/or the area for buried metallic objects or utilities.

(2) Similarly when the dual channel recorder is being used there should be no zero offset as described in 2.2.1 (b) and the meter reading set to zero using the COARSE and FINE controls as described in 2.1.2 (a).

A zero offset for negative inphase readings can however be allowed for on the recorder by setting the zero position of the pen at some arbitrary positive value when calibrating the recorder.

3. INSTRUMENT CALIBRATION

Prior to shipping, the instrument is calibrated in the factory to read properly. If necessary, calibration procedures are easily carried out as described below. IMPORTANT The most critical adjustment is the QF (quadrature fine) potentiometer which has been precisely adjusted at the factory.

Before any adjustments are made it is strongly recommended that the instrument first be set up at a fixed height over a known location and the ground conductivity carefully noted. If this adjustment is misaligned the instrument will have to be recalibrated over ground of known conductivity.

3.1 Null Calibration

The zero setting of the EM31 can be readily set by following the procedure described in section 2.1.1 (c).

3.2 Absolute Calibration

Absolute instrument calibration is easily achieved if an area of ground is available of known and constant conductivity down to the depth of penetration of the instrument. The procedure is simple; the instrument is located over the known area at the usual operating height (approximately 1m) and the QF compensation control is adjusted until the meter reads the correct terrain conductivity. If the ground conductivity is high the graph of Fig. 3 must be used to correctly set the instrument reading.

It is wise to maintain such an area as a calibration check area even if the variation of the conductivity with depth at that area is not accurately known. This is useful for cross checking with future measurements.

Note:

The QF and NULL controls are located under the front panel. Battery pack should be removed to have access.

4. SURVEY TECHNIQUE

Surveying with the EM31 is straightforward. As pointed out in a previous section, measurements may be made either continuously or on a station-by-station basis. In either case it is always recommended, as for any other geophysical survey, that survey lines and measurement stations be carefully laid out, and the survey performed in a systematic fashion with the resulting data accurately plotted for each measurement station. The most common survey error is to have the survey lines too short, in which case they do not extend sufficiently far off the supposedly anomalous region to permit the operator to establish the background values of terrain conductivity.

The EM31 yields good spatial resolution and measurement stations should be ten meters apart if the maximum resolution is to be employed. In many cases this spacing will be smaller than necessary, and twenty or perhaps forty meters will be adequate. The decision as to the correct spacing will be based on a knowledge of the lateral dimensions of the anticipated resistivity anomaly. To ensure the correct spacing it is useful, at the start of the survey, to continuously observe the conductivity values that are encountered as the operator moves down the survey line.

The resolution in conductivity of the EM31 is also high, with changes of 5% being quickly perceived. This instrument is capable of giving an extremely precise survey with information on small variations in the terrain conductivity.

4. SURVEY TECHNIQUE (cont'd)

It was seen in Section 1 that current flow within the earth consists of a series of concentric circles, assuming that the conductivity is laterally uniform. Therefore in the case of a uniform half-space, rotation of the instrument in a horizontal plane about the transmitter coil as a pivot will produce no change in the meter reading. Conversely, any change in the reading as this procedure is carried out is an indication of lateral inhomogeneities in conductivity. It is simpler and usually sufficiently accurate for the operator to rotate the instrument through 90° using himself as pivot at each measurement station. Thus if the lines are in a north-south direction the operator would normally walk along the line with the instrument pointing in a north-south direction; at each measurement station he can also take a reading with the instrument pointing east-west to check that this is essentially the same as the north-south reading. In the event that this reading is significantly different it may be worthwhile for the operator to then rotate the instrument to the points where the conductivity reading is both a maximum and a minimum, and to record both values. The average value can then be used for the data reduction.

The EM31 is somewhat sensitive to underground conductors such as large pipes, etc. These are usually easily recognized by the large meter fluctuations which occur within a short distance, as shown in Fig. 2. In an actual survey, since the negative-going peak is often off-scale, it is not possible to use it to locate the pipe; finding the point half way between the two positive-

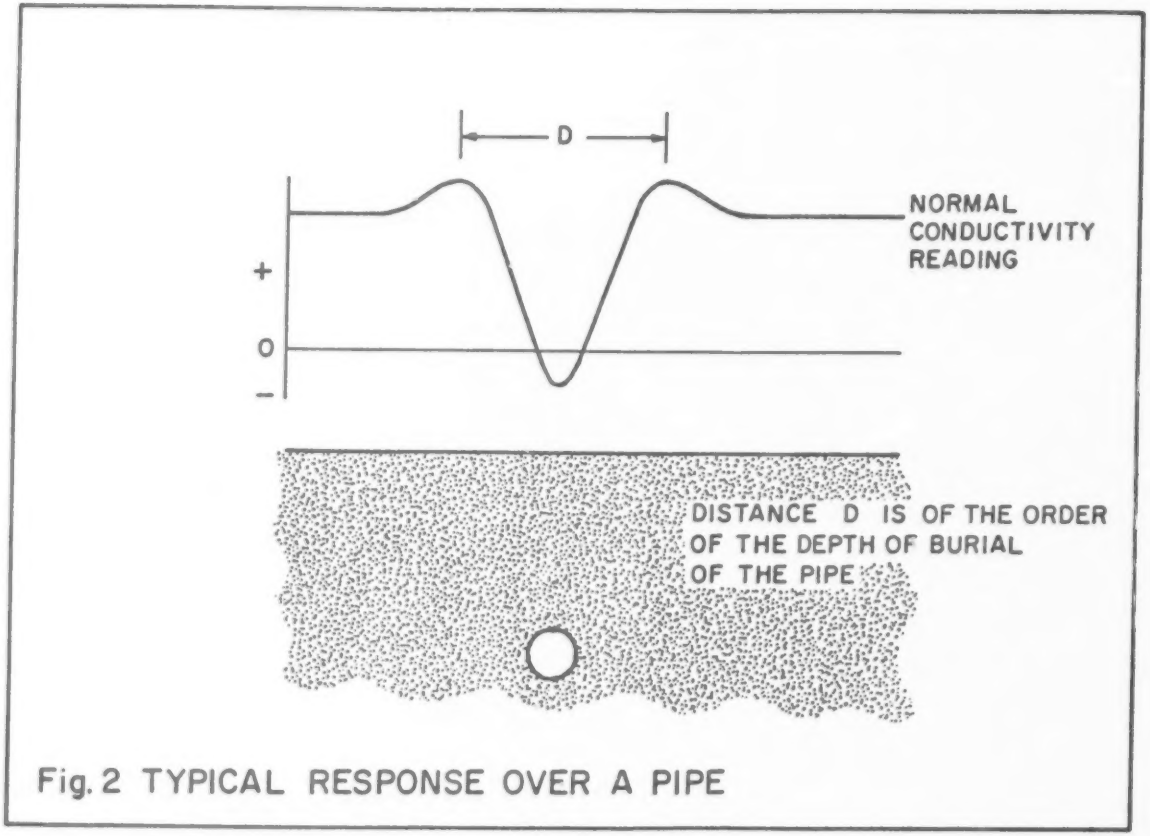


Fig. 2 TYPICAL RESPONSE OVER A PIPE

4. SURVEY TECHNIQUE (cont'd)

going peaks approximately performs the same task. It is then possible to accurately determine the location and strike direction (azimuth) of the conductor axis as follows: the approximate location is determined as above, and a traverse is then made over the conductor with the EM31 pointing in the approximate direction of the conductor axis. The meter reading will now be a positive maximum when the instrument is both directly over the conductor and pointing accurately along the conductor axis.

The instrument is relatively unaffected by fences, overhead power lines, and other nearby metallic objects. In order to determine whether the reading is influenced by such structures the operator should rotate the instrument to check for changes in reading, becoming suspicious if a maximum or minimum occurs when the instrument points either perpendicular or parallel to the structure. Before recording the measurement the operator should move away from the structure until no evidence of lateral inhomogeneity is seen when the instrument is rotated.

It should be remembered that the EM31 is an electromagnetic tool and care should be taken near obvious conductors until the operator has satisfied himself as to their possible affect. In every case this is determined by rotating the instrument and determining whether there is a maximum and minimum which appears to be realted to the structure. If a structure is giving such an effect it is not advisable to take the average value of the two readings as an indicator of the terrain conductivity.

4. SURVEY TECHNIQUE (cont'd)

In general the conductivity readings obtained with the EM31 will vary smoothly from one region to another. In some cases however, as for example where a well defined vertical contact separates a poor conductor from a very good conductor, edge effects may be seen in which the readings vary rapidly with position and are no longer a good indicator of the terrain conductivity. Edge effects may also occur where a very good conductor (a few ohm-meters or less) has dimensions of the order of the inter-coil spacing, and again the indicated readings may not accurately reflect the true terrain conductivity. In any circumstance where the apparent conductivity varies significantly in a distance which is short compared with the intercoil spacing the possible presence of edge ef-fects or local subsurface conductors must be considered.

Finally, particularly during mid-summer afternoons, electrical static (electromagnetic radiation from local or distant thunderstorms) may cause the meter readings to become noisy. This is usually evidenced by sudden flicks of the meter needle, however in very severe cases the meter may simply wander about an average reading. Should this occur it is recommended that measurements cease until the "spherics" are over, usually later in the afternoon. Similarly, noisy readings may also be noted when making measurements near large power lines.

5. DATA INTERPRETATION

5.1 Uniform Halfspace

The EM31 has been designed to operate over a range of resistivities from a few ohm-meters to thousands of ohm-meters. For smaller resistivities the instrumental response departs from linearity as shown in Fig. 3, where it will be seen that up to one hundred millimhos per meter the indicated conductivity (σ_a) closely approximates the true conductivity. A departure from linearity is evident for true conductivity greater than one hundred millimhos per meter and beyond one thousand millimhos per meter the instrument response decreases with increasing conductivity. As stated in the introduction, it is generally more informative to observe the spatial variations of terrain conductivity rather than the absolute value of conductivity itself. Fig. 3 shows that as long as the terrain conductivity does not fall below five hundred millimhos per meter (2 ohm-meters) the instrument will be adequately sensitive to small changes in conductivity although it does not read the actual value of conductivity accurately. If necessary, Fig. 3 can be used to correct values of indicated conductivity to actual conductivity.

It should be noted that the graph refers to the worst case viz that of the uniform halfspace. If only a portion of the subsurface ground beneath the instrument is of high conductivity as in the case of horizontal layering, the influence of the high conductivity layers will be proportionately reduced and the indicated conductivity will accurately read the "apparent conductivity" as defined in the following section.

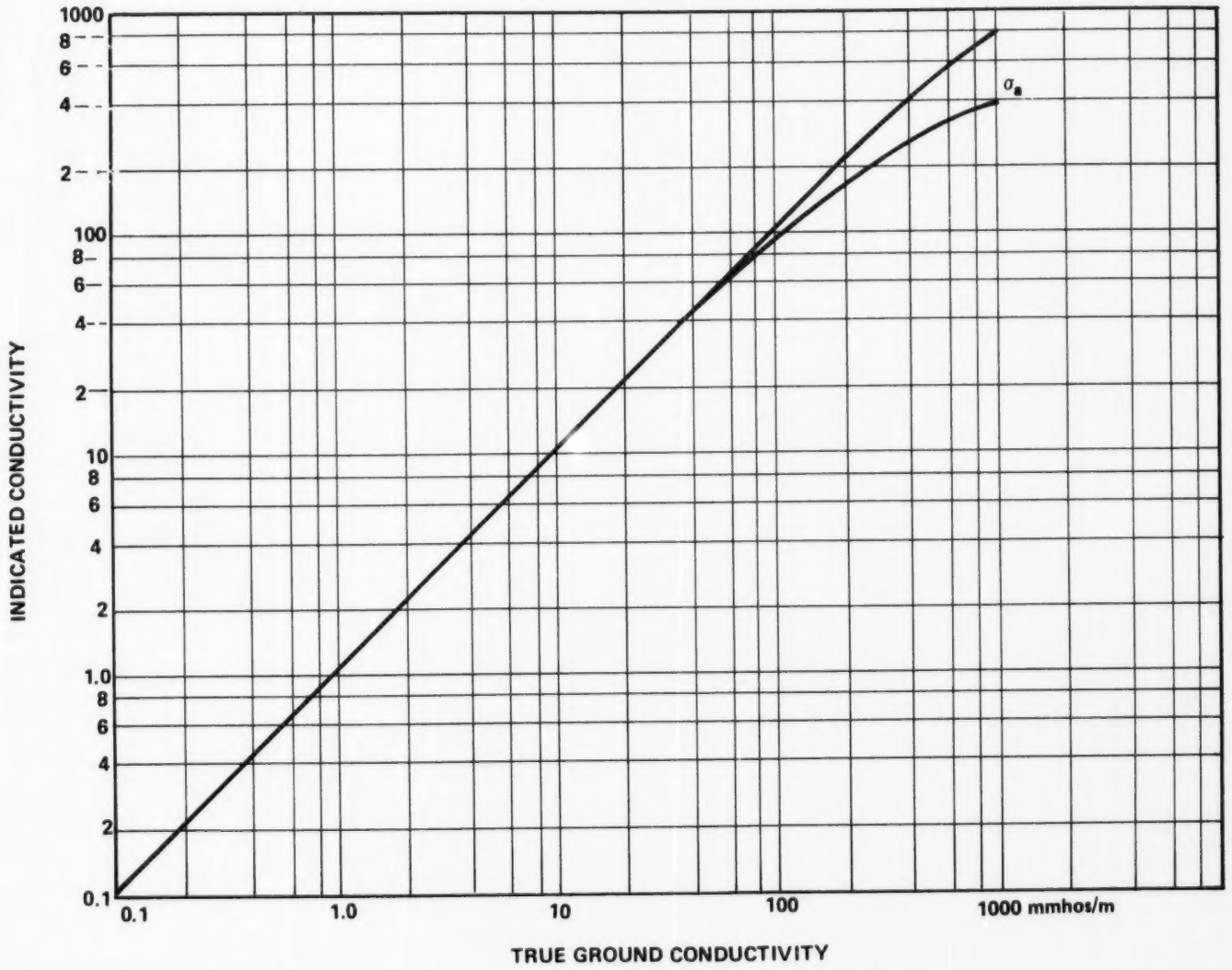

1000
8
6
4
2
100
8
6
4
2
10
8
6
4
2
1.0
8
6
4
2
0.1
σ_a
INDICATED CONDUCTIVITY
0.1
1.0
10
100
1000 mmhos/m
TRUE GROUND CONDUCTIVITY

Figure 3

5.2 Multi-Layered Earth

A geophysical model that is of particular importance is the horizontally layered earth, and the EM31 allows a very simple interpretive technique for this model. In order to utilize the model the terrain layering must be well defined and constant over a lateral distance of at least five meters in any direction from the instrument. This condition is often satisfied and this fact is responsible for the usefulness of the technique described herein.

Fig. 4 is a plot of "R(Z)", a function which describes the cumulative relative contribution of all of the material below a depth Z to the instrument reading. Thus if we multiply this function by one hundred (so as to yield percent) all of the ground below a depth of two meters yields 59% of the response, the ground below three meters yields 47%, the ground below six meters yields 29%, etc., assuming that the conductivity itself does not vary with depth.

The algebraic expression given on the figure illustrates the technique which is used to calculate the "apparent conductivity" that will be measured by the instrument for any number of layers, for any values of conductivity and for any thicknesses. Consider for example Fig. 5, which illustrates in cross section a buried river valley cut into shale and subsequently infilled with glacial till. We wish to calculate the instrument response as such a structure is traversed. This is a two layer problem and the expression for the apparent conductivity reduces to:

$$\frac{\sigma_a}{\sigma_1} = 1.000 - R(Z_1) + k_2 R(Z_1) \qquad (1)$$

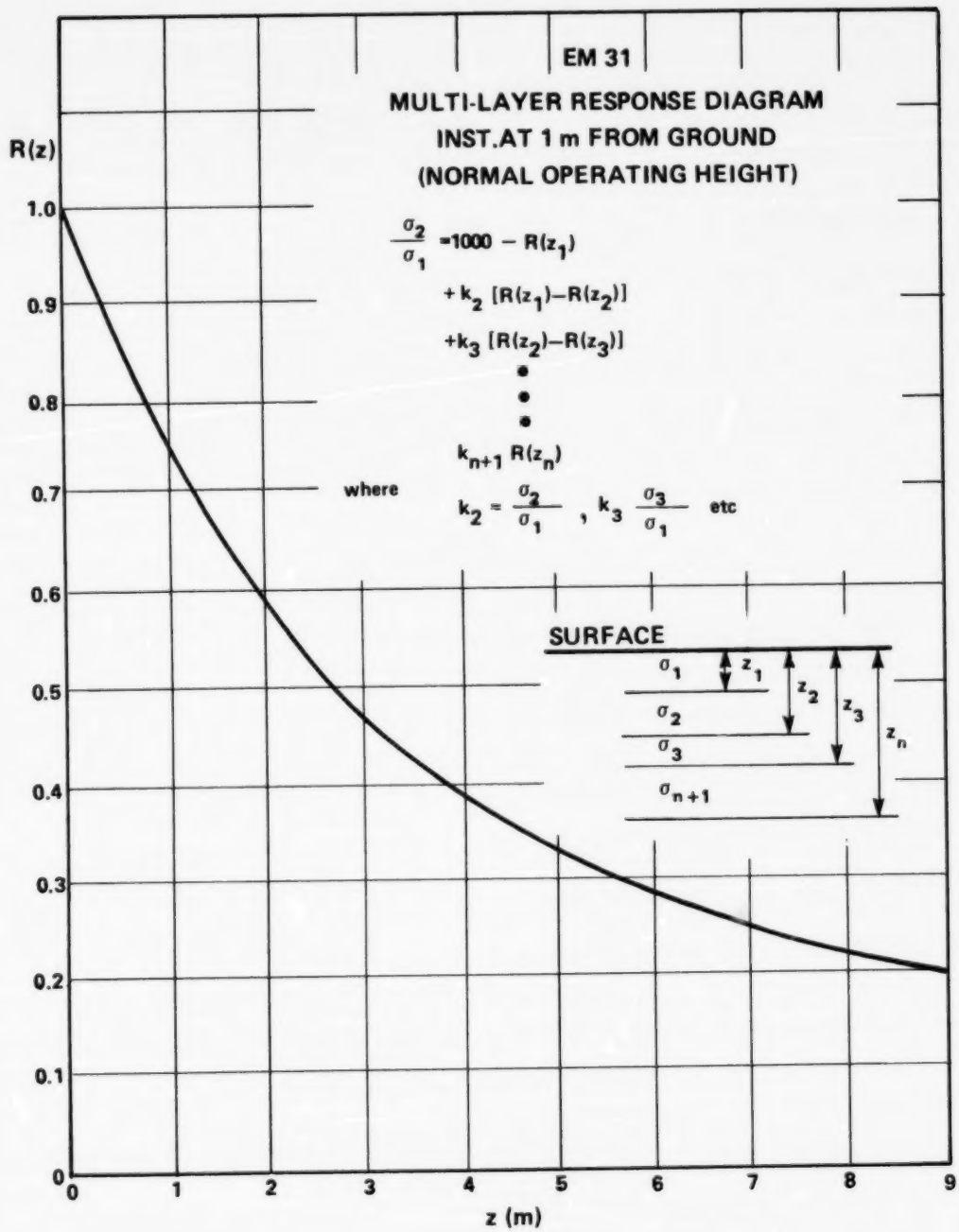

EM 31
MULTI-LAYER RESPONSE DIAGRAM
INST.AT 1 m FROM GROUND
(NORMAL OPERATING HEIGHT)
$\frac{\sigma_2}{\sigma_1}$ =1000 − R(z1)
+k2 [R(z1)−R(z2)]
+k3 [R(z2)−R(z3)]
•
•
•
kn+1 R(zn)
where
$k_2 = \frac{\sigma_2}{\sigma_1}$, $k_3 \frac{\sigma_3}{\sigma_1}$ etc
SURFACE
σ1
σ2
σ3
σn+1
z1
z2
z3
zn
R(z)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9
z (m)

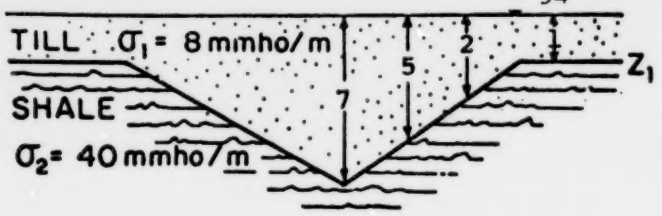
Figure 4

5.2 Multi-Layered Earth (cont'd)

The table accompanying the figure shows the calculations which yield the value of apparent conductivity at various thicknesses of the upper layer. Thus as we traverse such a structure we would find that the apparent conductivity fell from 32.6 millimhos per meter at a large distance from the buried river valley to 16.0 millimhos per meter at the center of the valley.

Fig. 6 illustrates a second situation where now the objective is to locate bedrock highs within muskeg. This is again a two layer case and the table illustrates the calculations to determine the apparent conductivity. For this configuration, i.e. a conductor on top of an insulator and k_2 a small quantity, the measured apparent conductivity becomes relatively independent of the actual value of the conductivity of the lower layer. For $k_2 << 1$, the apparent conductivity simply becomes a function of the thickness of the upper conductive layer.

Finally a third example is given in Fig. 7. In this case we wish to traverse a thickening gravel deposit; the maximum thickness is such that the instrument still responds to material below the deposit. This is an example of the situation of an insulator sandwiched between two conductors and is inevitably the most difficult geometry for electromagnetic systems to detect, as evidenced by the tabulated values of apparent conductivity. Even at a thickness of five meters (station D) there is still significant response from the till beneath the deposit and this response tends to keep the apparent conductivities high.

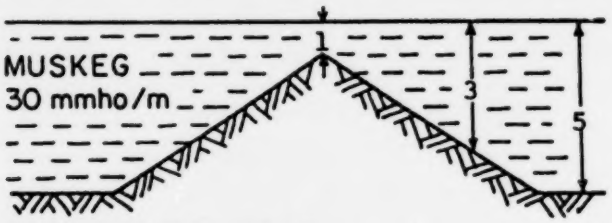


$$\frac{\sigma_a}{\sigma_1} = 1.000 - R(Z_1) + k_2 R(Z_1) \qquad (1)$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{40}{8} = 5$$

Z_1 = 1m, σ_a = 8(1.00 - 0.77 + (5 x 0.77)) = 32.6 mmho/m
Z_1 = 2m, σ_a = 8(1.00 - 0.59 + (5 x 0.59)) = 26.9 "
Z_1 = 5m, σ_a = 8(1.00 - 0.33 + (5 x 0.33)) = 18.6 "
Z_1 = 7m, σ_a = 8(1.00 - 0.25 + (5 x 0.25)) = 16.0 "

Fig. 5 CROSS SECTION BURIED RIVER VALLEY

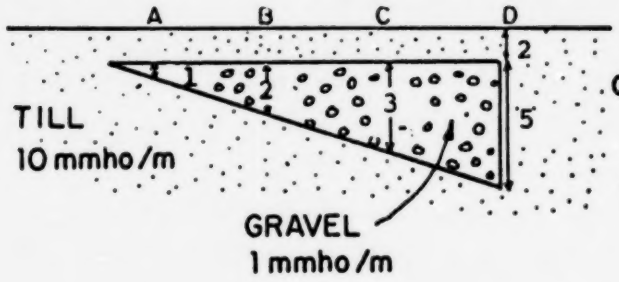


$$\frac{\sigma_a}{\sigma_1} = 1.000 - R(Z_1) + k_2 R(Z_1)$$

$$k_2 = \frac{0.1}{30} = 0.0033$$

Z_1 = 5m, σ_a = 30(1.00 - 0.33) = 20.1 mmho/m
Z_1 = 3m, σ_a = 30(1.00 - 0.47) = 15.9 "
Z_1 = 1m, σ_a = 30(1.00 - 0.77) = 6.9 "

Fig. 6 CROSS SECTION BEDROCK HIGH



$$\sigma_a = \sigma_1 [1.000 - R(Z_1) + k_2 R(Z_1) - k_2 R(Z_2) + k_3 R(Z_2)]$$

$$k_2 = \frac{\sigma_2}{\sigma_1} = \frac{1}{10} = 0.10$$

$$k_3 = \frac{\sigma_3}{\sigma_1} = 1.00$$

(A) σ_a=10 (1.00-0.59+(0.10x0.59)-(0.10x0.47)+(1.00x0.47)) = 8.9 mmho/m
(B) σ_a=10 (1.00-0.59+(0.10x0.59)-(0.10x0.39)+(1.00x0.39)) = 8.2 "
(C) σ_a=10 (1.00-0.59+(0.10x0.59)-(0.10x0.33)+(1.00x0.33)) = 7.7 "
(D) σ_a=10 (1.00-0.59+(0.10x0.59)-(0.10x0.25)+(1.00x0.25)) = 6.9 "

Fig. 7 CROSS SECTION GRAVEL DEPOSIT

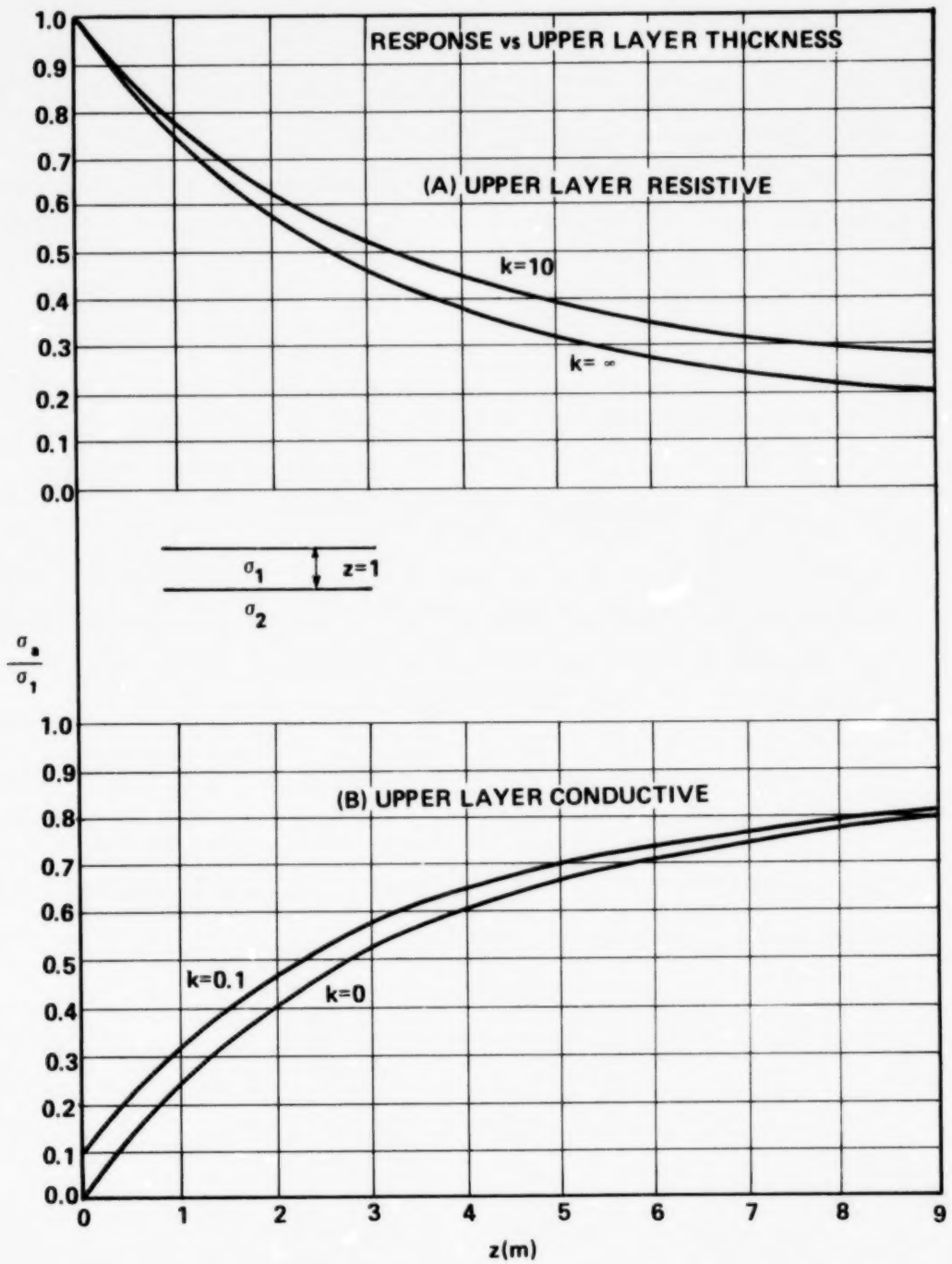

RESPONSE vs UPPER LAYER THICKNESS
(A) UPPER LAYER RESISTIVE
k=10
k= ∞
σ1
z=1
σ2
σa/σ1
(B) UPPER LAYER CONDUCTIVE
k=0.1
k=0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8
9
z(m)

Figure 8

5.2 Multi-Layered Earth (cont'd)

The three examples show how to calculate the response of the EM31 over a variety of geological environments. Since the instrument operates at a fixed intercoil spacing it is not possible to completely "sound" or evaluate differing conductivity layers with depth. Section 5.3 will show how to further resolve the two-layer case, however it is always useful to be able to calculate the apparent conductivity which would arise from a given multi-layer model to see whether that model fits the measured data.

Fig. 8 shows the apparent conductivity over the two limiting cases of a two layer geometry where the conductivity contrast is very large. In Fig. 8A the upper layer is assumed to be very resistive and the figure shows the apparent conductivity with respect to the lower layer conductivity (assumed known) as a function of the depth below the surface of the lower layer, for values of k of ten and infinity. Thus for large k the figure permits the operator to quickly convert the measured values of apparent conductivity to depth, and to estimate the error if the conductivity contrast is not infinite.

Fig. 8B performs the same task for small values of conductivity contrast. It should be noted that Fig. 8B plots the apparent conductivity with respect to the upper layer conductivity.

It is stated in the data sheet that the effective depth of penetration of the EM31 is approximately six meters. Justification for this claim is shown in Fig. 8 where it is seen that for either a resistive ($k = \infty$) or conductive ($k = 0$) upper layer the apparent conductivity is still

5.2 Multi-Layered Earth (cont'd)

satisfactorily sensitive to changes in the upper layer thickness at six meters. The limitation in resolving further changes in thickness is imposed by probable variations in the conductivity of either layer.

5.3 Geometrical Sounding of Two Layered Earth

It is possible with the EM31 to determine whether the conductivity increases or decreases with depth by laying the instrument on the ground, noting the reading, and then placing the instrument on its side so that the meter face is vertical and again noting the instrument reading. The reason for this is that when the instrument is on its side the new transmitter and receiver coil orientation with respect to the earth causes the effective depth of penetration of the instrument to be essentially halved. It should be noted that in this configuration the current flow does not exhibit the circular symmetry shown in Fig. 1. Thus let σ_a be the apparent conductivity indicated by the instrument on the ground in its normal operating position and let σ_a' be the apparent conductivity indicated when the instrument is lying on its side. If σ_a is greater than σ_a' we know that the conductivity is increasing with depth and vice versa. The ability of the EM31 to indicate whether the conductivity is increasing or decreasing with depth is often of considerable diagnostic value.

It will be observed from the above that it is now possible to obtain two measured quantities at each measurement station. In the event that the earth consists only of two layers, there are three unknown quantities i.e.

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

the conductivity of the upper and lower layer and the thickness of the upper layer. If one of these is known it is possible, using the technique described above, to determine the other two. More importantly, when there is a large conductivity contrast so that the conductivity of either the upper or lower layer can be ignored with respect to the other layer then it is possible to completely resolve the two layered earth. An example of the importance of this can be seen in Fig. 8 which gives the instrumental response as a function of upper layer thickness for either a resistive or conductive upper layer. In order to use these graphs it is necessary to know the conductivity of the lower or upper layer respectively, since both graphs are normalized with respect to these quantities. An inaccurate knowledge of σ_2 in the case of a resistive upper layer or σ_1 in the case of a conductive upper layer can result in a substantial error in the calculated thickness of the upper layer. Any technique which allows us to determine the conductivity of the more conductive layer is of considerable importance since by definition the EM31 is most useful when one layer presents a significant conductivity contrast with respect to the other.

Fig. 9 shows a multi-layer response diagram R(Z), completely analogous to Fig. 4 but with the instrument now laying on the ground. Fig. 10, which presents the function R'(Z) as a function of depth is the same function as Fig. 9 but now with the instrument rotated on its side so that the meter face is vertical. It will be noted from Fig. 9 that with the instrument on the ground in its normal operating configuration the total contribution from

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

all ground in excess of a depth of five meters is 34% whereas Fig. 10 shows that with the instrument lying on its side the ground in excess of five meters causes a total contribution of only 17.5% of the total response. This is the justification for stating earlier that the instrument has effectively one half the depth penetration when lying on its side. Fig. 9 also contains a plot of the ratio R'/R and Fig. 10 a plot of the ratio (1-R')/(1-R), both as a function of depth.

Case 1. σ_1 and σ_2 comparable and σ_1 known. It is shown in Appendix 1 that for this case

$$\frac{R'(Z)}{R(Z)} = \frac{\frac{\sigma_a'}{\sigma_1} - 1}{\frac{\sigma_a}{\sigma_1} - 1}, \qquad \sigma_2 = \frac{\sigma_a - \sigma_1 + R\sigma_1}{R} = \frac{\sigma_a' - \sigma_1 + R'\sigma_1}{R'}$$

thus given σ_a', σ_a, and σ_1, R'/R is calculated; Fig. 9 then gives the thickness of the upper layer as a function of R'/R; with this thickness Fig. 9 or 10 is used to determine R or R' and the second equation given above is used to determine σ_2 thus fully resolving the two layer case.

Case 2. σ_1 and σ_2 comparable and σ_2 known. In this case Appendix 1 shows that

$$\frac{1 - R'(Z)}{1 - R(Z)} = \frac{\frac{\sigma_a'}{\sigma_2} - 1}{\frac{\sigma_a}{\sigma_2} - 1}, \qquad \sigma_1 = \frac{\sigma_a - \sigma_2 R}{1 - R} = \frac{\sigma_a' - \sigma_2 R'}{1 - R'}$$

5.3 Geometrical Sounding of Two Layered Earth (cont'd)

Knowing σ_a', σ_a, and σ_2, $(1-R')/(1-R)$ is calculated, Fig. 10 gives the thickness and given the thickness Fig. 9 or 10 gives R or R' so that the second equation given above is used to calculate σ_1.

Case 3. Upper layer resistive. σ_1 much less than σ_2. In this case Appendix 1 shows that

$$\frac{R'(Z)}{R(Z)} = \frac{\sigma_a'}{\sigma_a}, \qquad \sigma_2 = \frac{\sigma_a}{R} = \frac{\sigma_a'}{R'}$$

and the same proceedure as for Case 1 above is used to determine the thickness of the upper layer and the conductivity of the lower layer.

Case 4. Upper layer conductive. σ_1 much greater than σ_2. Again Appendix 1 shows that

$$\frac{1 - R'(Z)}{1 - R(Z)} = \frac{\sigma_a'}{\sigma_a}, \qquad \sigma_1 = \frac{\sigma_a}{1 - R} = \frac{\sigma_a'}{1-R'}$$

and the calculations for Case 2 yield the thickness and the conductivity of the upper layer.

To illustrate the above let it be assumed that the upper layer is known to be 10 millimhos per meter and the EM31 indicates 3.8 millimhos per meter when laying on the ground in its normal configuration and 6.5 millimhos per meter when lying on its side. Fig. 3, which also gives the correction factor to use when the instrument is lying on its side, shows that no correction is necessary.

5.3 Geometrical Sounding of Two-Layered Earth (cont'd)

Since the instrument has been calibrated to be operated at one meter above the ground both of these numbers must be multiplied by .88 since the instrument is being used on the ground. This results in σ_a = 3.3 millimhos per meter and σ_a' = 5.7 millimhos per meter. Then

$$\frac{R'(Z)}{R(Z)} = \frac{\frac{\sigma_a'}{\sigma_1} - 1}{\frac{\sigma_a}{\sigma_1} - 1} = \frac{\frac{5.7}{10} - 1}{\frac{3.3}{10} - 1} = 0.64$$

whereupon Fig. 9 shows that the thickness of the upper layer is 1.25 meters and R(Z) = 0.825 whereupon

$$\sigma_2 = \frac{\sigma_a - \sigma_1 + R\sigma_1}{R} = \frac{3.3 - 10 + 0.825 \times 10}{0.825} = 1.9$$

The technique for the other cases described above is exactly the same.

The calculations described above assume that the earth is known to be two-layered. It is possible to determine whether this is true by measuring the apparent conductivity with the EM31 elevated to various heights above the ground and comparing the results with a family of curves given in Appendix II. If the measured variation of apparent conductivity with height matches one of the curves, one can immediately calculate the conductivity of both layers and the thickness of the upper layer, as described therein.

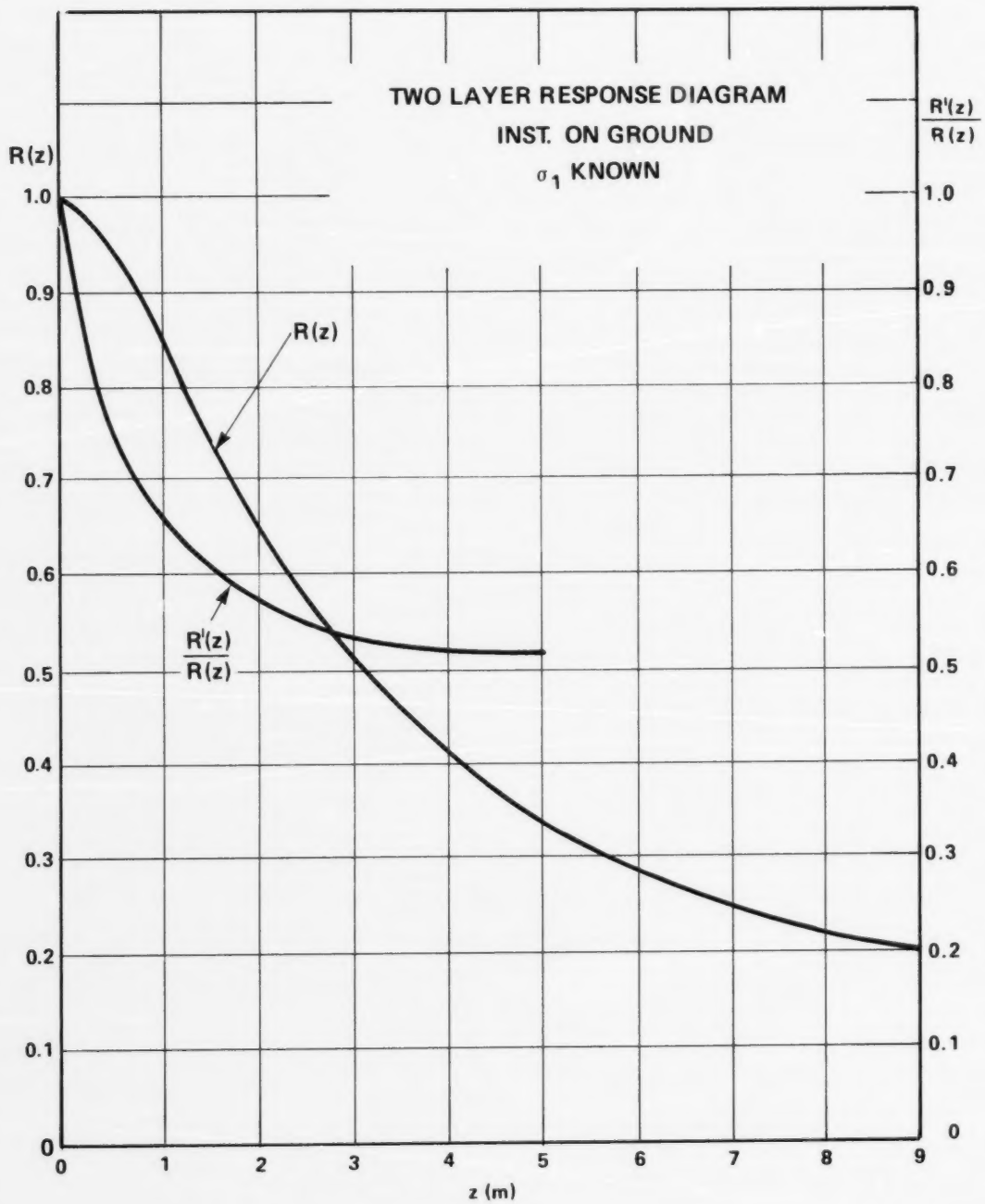

TWO LAYER RESPONSE DIAGRAM
INST. ON GROUND
σ_1 KNOWN
R(z)
$\frac{R'(z)}{R(z)}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
R(z)
$\frac{R'(z)}{R(z)}$
0
1
2
3
4
5
6
7
8
9
z (m)

Figure 9

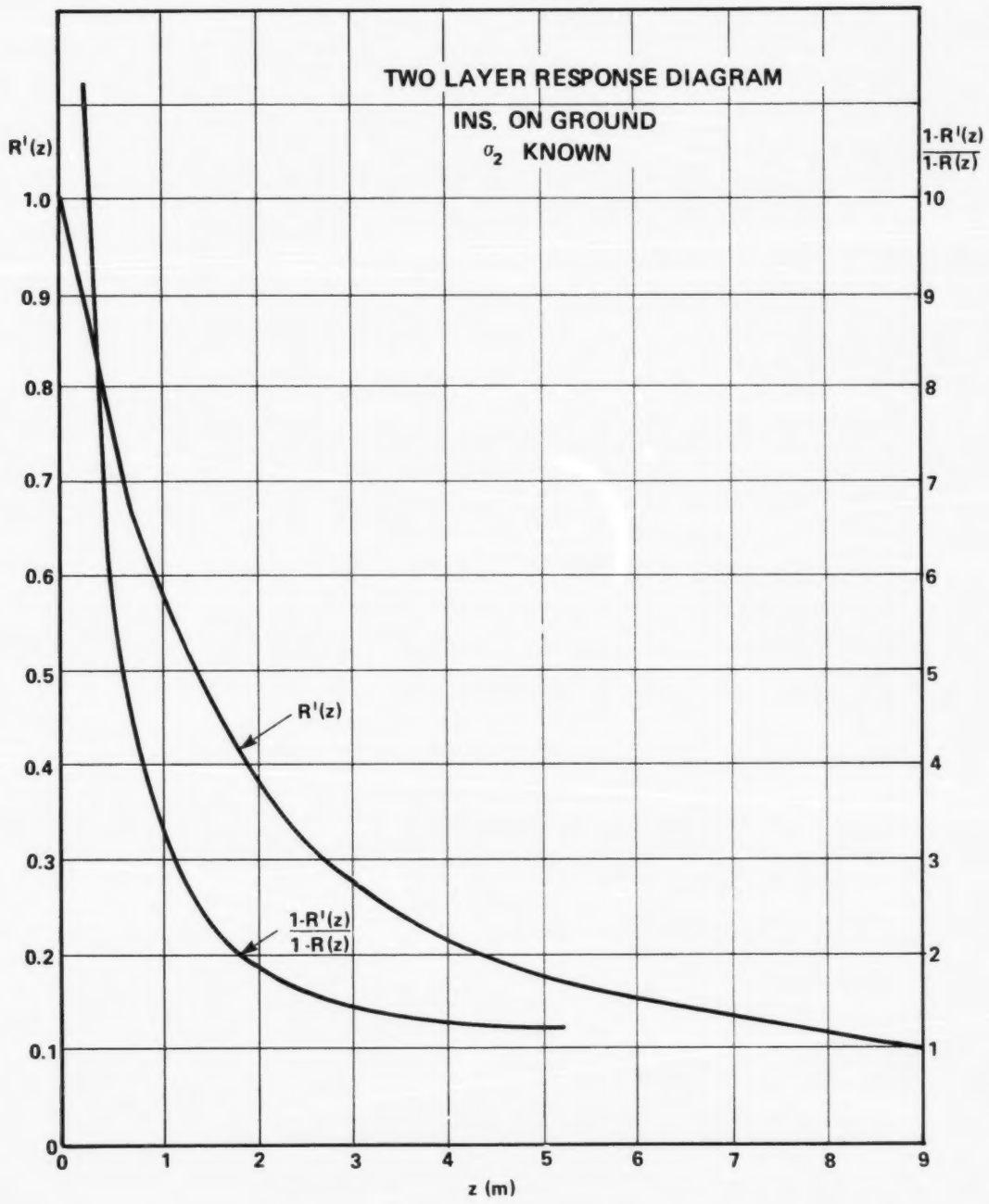

TWO LAYER RESPONSE DIAGRAM
INS. ON GROUND
σ_2 KNOWN
R'(z)
$\frac{1-R'(z)}{1-R(z)}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
z (m)
R'(z)
$\frac{1-R'(z)}{1-R(z)}$

Figure 10

EM31 RECORDER OUTPUT SENSITIVITY NOTE

PIN ASSIGNMENT

Quadrature component	-	Pin A
In-Phase component	-	Pin C
Common	-	Pin B

QUADRATURE COMPONENT OUTPUT

Range switch Position (millimhos/m)	Full Scale Voltage - Pin "A" (mV)
1000	500
300	500
100	500
30	500
10	500
3	500

IN-PHASE COMPONENT OUTPUT

1000 mV ≡ 23%

1% ≡ 43.5 mV Regardless of scale used

Geonics Limited

February, 1984.

CALIBRATING THE EM31 RECORDER
(Watanabe SR 6421)

1. Complete the EM31 functional checks as described in Section 3.1 of the EM31 Operating Manual.

2. With recorder on, and connected to the EM31 but with the EM31 off, rotate the Position knob of the recorder setting the pen at the Zero position at the left-hand side on the chart paper.

3. Set the recorder sensitivity (Range Switch) to 500 mv.

4. Turn the EM31 on and set the EM31 Range Switch to 10, 100, or 1,000 millimhos/m whichever gives the largest meter deflection in location at hand. (e.g. for an apparent conductivity of 28 mmhos/m the Range Switch on the EM31 would be set at 100 mmhos/m.

5. Using the Vernier adjustment, set the pen position to read the same number of divisions (to the right of the Zero position) as the EM31 meter reading in mmhos/m (ms/m).

   The full scale deflection on the chart paper will now correspond to full scale deflection of the EM31 meter.

NOTE (1) Thus, if during the survey the apparent ground conductivity increased to say 150 mmhos/m and the EM31 Range Switch is switched to the 300 mmhos/m position, then the full scale deflection on the chart paper will correspond to 300 mmhos/m and the 150 mmhos/m reading on the meter will give a corresponding reading of 50 divisions on the chart paper.

(2) The Zero position on the chart paper can be set at any preferred position and the full scale meter deflection correspond to any number of divisions selected (e.g. if negative readings are desired then the Zero position could be set at say 50 divisions in Step 2 and the full scale meter deflection 0 to 100 mmhos/m would be recorded by 50 divisions on the chart paper from 50 to 100 divisions. Negative readings would be from 50 to 0 on the chart paper.

Geonics Limited
December, 1983.

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EM34-3 OPERATING INSTRUCTIONS

The following is the set-up and operating procedure for the EM34-3 Terrain Conductivity Meter.

1. INITIAL SET-UP At the beginning of the survey select an area free of "cultural interference" and man-made conductors such as buried pipes, buildings, power lines and steel reinforced concrete, etc.

1.1 Having determined the coil separation to be used for the survey, lay the instrument out on the ground accordingly. Connect the reference cable (10, 20 or 40 meters) - one end to the 8-pin connector on the transmitter (Tx) coil and the other end to the "REFERENCE" connector on the receiver console. See attached sketch for proper use of thimbles and snaps on the cable.

1.2 Connect the transmitter console to the transmitter coil using the appropriate short cable.

1.3 Put the "LEVEL" switch on the transmitter console to the "NORMAL" position. (See Section 6.)

1.4 Set the receiver and transmitter coils to the selected coil separation with red circles on the coils both facing in the same direction.

1.5 Set transmitter "SEPARATION" switch to selected value and turn on trasmitter (POWER/OFF" switch to "POWER" position).

1.6 Check to see that Battery Monitor Meter indicator is in the black area of the scale. If not, batteries are low or are not making proper contact to the battery clips.

1.7 Check condition of receiver battery by rotating receiver "SEPARATION" switch to "BATT" position with "POWER/OFF" switch in "OFF" position (see Section 5.2).

1.8 Set receiver "SEPARATION" switch to selected value.

2. ELECTRONIC NULLING To remove any offsets in the output (DC) circuitry.

2.1 Prior to turning receiver on, insure that meters read zero by adjusting mechanical meter zero control.

2.2 Turn on receiver ("POWER/OFF" switch to "POWER" position).

2.3 With receiver coil disconnected depress "NULL MODE" push button switch. Both meter needles should go to zero.

2.4 If either needle is not at zero reading, release the lock on the appropriate "NULL" control potentiometer. With "NULL MODE" switch still depressed adjust the "NULL" control to zero the meter.

2.5 Lock the "NULL" control.

2.6 Connect the receiver coil to the receiver console "COIL" connector via the appropriate short cable.

3. RECEIVER COMPENSATION AND GAIN CHECK

3.1 Maintaining the receiver and transmitter coils in the same plane adjust the coil separation to obtain zero reading (centre of green area) on the "COIL SEPARATION" meter. (Insure that red circles on coils face in the same direction.) The coil separation should now measure the selected value and allow from 2-4 meters of slack reference cable between the thimbles which attach to the console leather cases.

3.2 With the "SENSITIVITY RANGE" switch set to the 300 millimho/meter position move the receiver coil toward the transmitter until the "COIL SEPARATION" meter deflects to full scale mark.

3.3 Measure the distance that the receiver coil has moved. This distance should be 10.4% of intercoil spacing.

4. TAKING A READING The instrument is now operational, reading apparent terrain conductivity directly in millimhos/meter in either the horizontal or vertical dipole mode.

4.1 At each measurement station the transmitter operator positions himself and remains stationary. The receiver operator should position the receiver coil such that the "COIL SEPARATION" meter is in the green area.

4.2 The "SENSITIVITY RANGE" switch should be set to the position which positions the "CONDUCTIVITY" reading in the upper 70% of the scale. The meter reading should then be recorded in millimhos/meter. (The "SENSITIVITY RANGE" switch setting indicates full scale meter reading.)

NOTE: In order to minimize reading errors particularly on the most sensitive settings it is necessary to keep the receiver and transmitter consoles separated from their respective coils by 0.7 - 1.0 meter.

5. PERIODIC DAILY CHECKS

5.1 Nulling: To make sure that any possible drift is kept under control, we suggest that you repeat the electronic nulling procedure (steps 2.1 to 2.6) at least once per day during the survey.

5.2 Receiver Battery Check: The receiver battery test is done simply by switching the "SEPARATION" switch to "BATT" position and power switch to "OFF" position. The meters will indicate the condition of the two sets of receiver batteries. If the indicator is below the markings replace the batteries, or see that the battery contacts are clean.

With new batteries, meter reading could be on the upper limit of the scale.

5.3 Transmitter Batteries: With the Tx coil connected and the "LEVEL" switch in the "HIGH" position, needle of the Battery Monitor Meter should be in the black area of the scale. Keeping the transmitter batteries warm in cold weather will improve battery lifetime.

6. TRANSMITTER OUTPUT POWER

As earlier mentioned transmitter output power should be kept at the "NORMAL" level for increased battery life. Under very noisy conditions (power line or spherics) the transmitter power should be increased by switching the "LEVEL" switch to "HIGH" position.

7. INSTRUMENT CALIBRATION

Prior to leaving the factory, the instrument is calibrated to read correctly, but due to its high sensitivity, fine adjustment of the instrument in the field may be helpful, particularly in regions of low conductivity and where the conductivity values are known to a good degree of confidence.

NOTE: As a precautionary measure the readings and exact location should be recorded prior to making any adjustments so that if the correction is found to be unsatisfactory the original settings can be recovered without returning the instrument to the factory.

7.1 Having decided what the new reading should be, the instrument "zero" can be adjusted by controls inside the receiver console. To gain access to these controls remove the receiver chassis from its metal cover by undoing the two side screws and battery lid.

7.2 The "zero" adjustment potentiometers are located on printed circuit board No.5 - one potentiometer for each coil separation.

10 meters - R15
20 meters - R14
40 meters - R13

7.3 The appropriate potentiometer should then be adjusted to give the desired meter reading.

NOTE: Each control should be adjusted only with the corresponding coil separation.

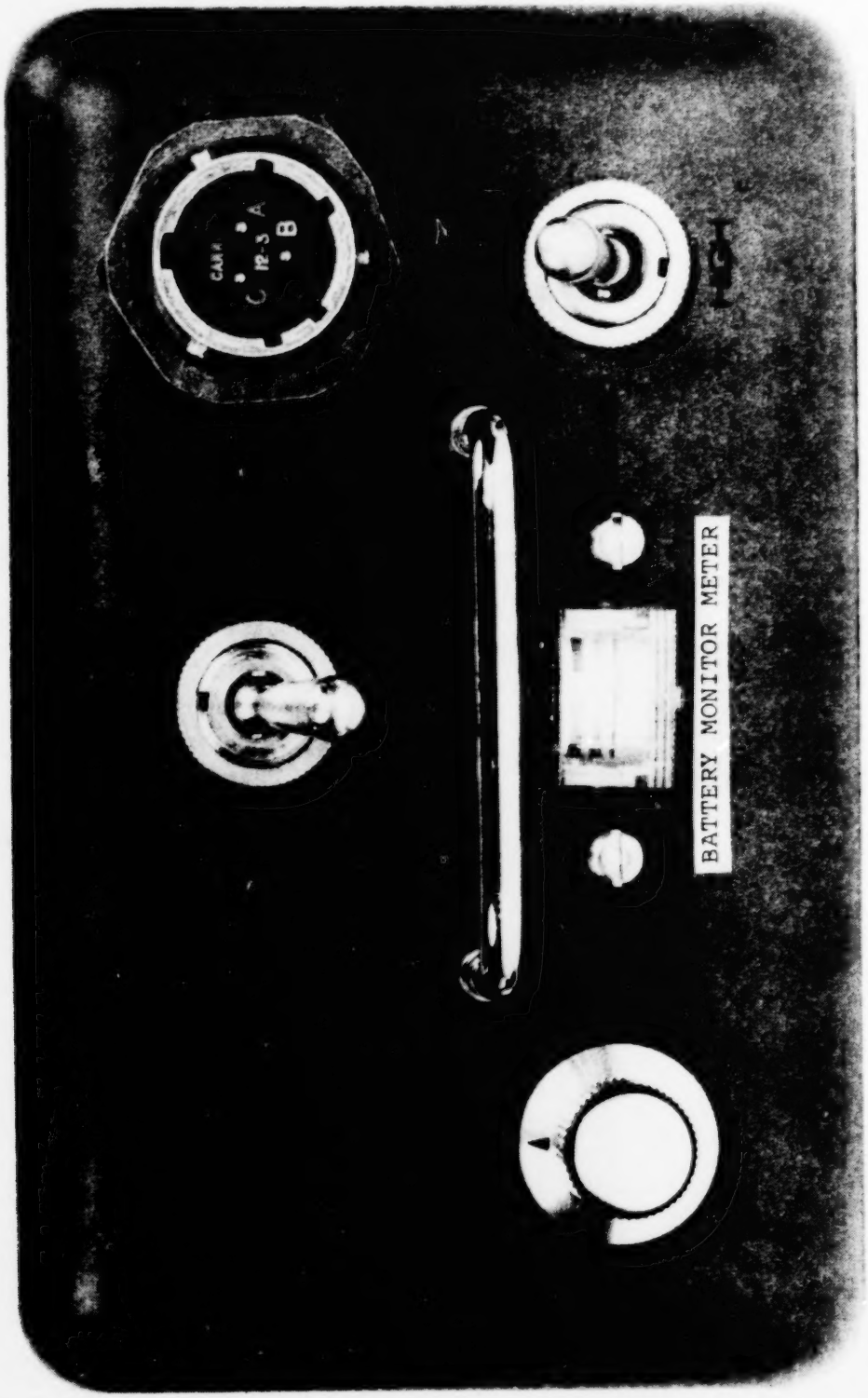
7.4 After adjusting any of the "zero" controls check the Electronic Null (Section 2). Re-Null is necessary and repeat "zero" adjustment.

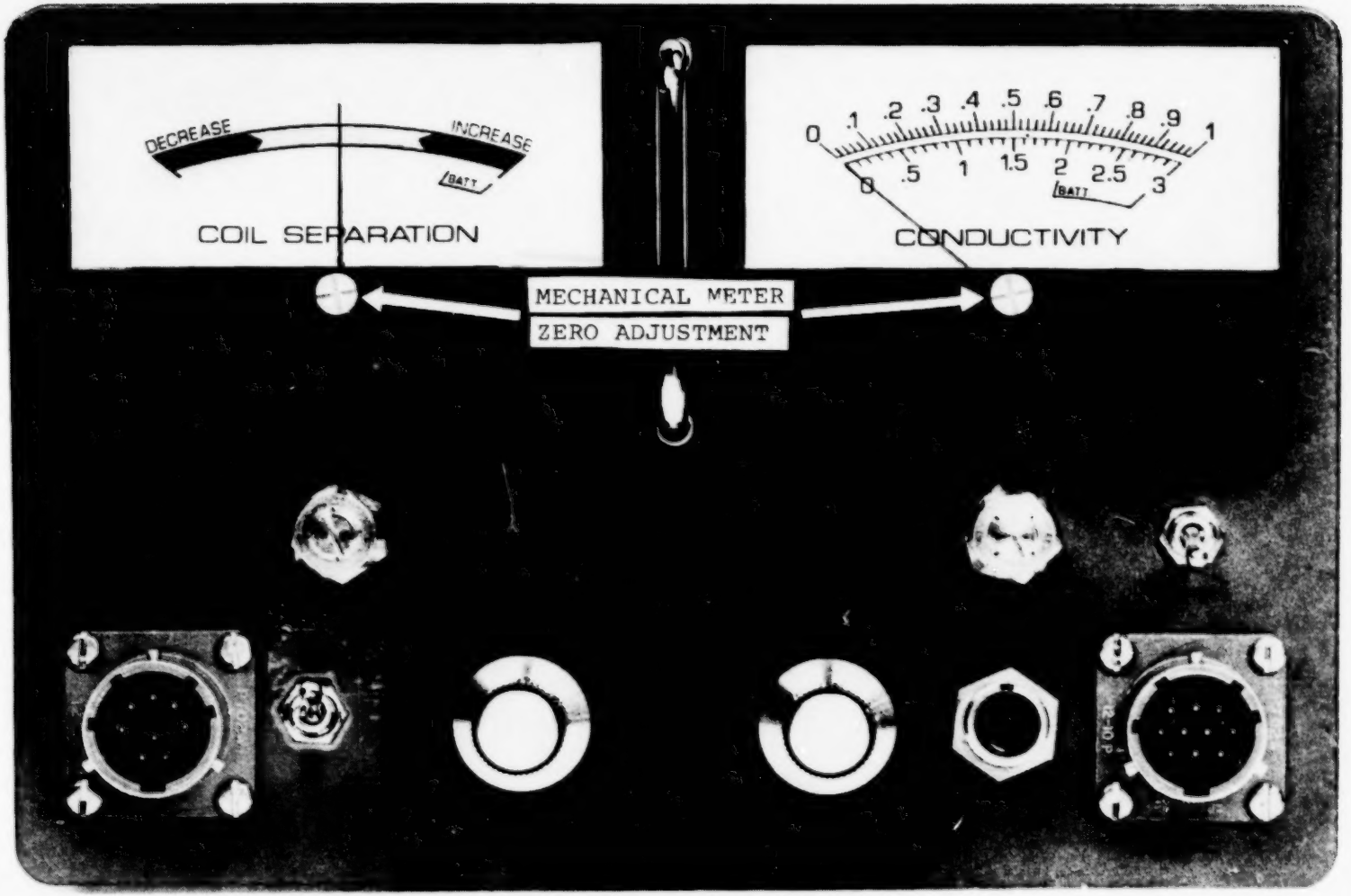
7.5 The switch with positions "N" (normal) and "R" (reversed), which is not shown on the accompanying illustration, is used to reverse the meter deflection. This switch is operated when the meter deflects negatively as may occur when traversing vertical dikes.

EM34-3 INSTRUMENT SPECIFICATIONS

Measured Quantity	Apparent conductivity of the ground, in mS/meter (divided into 1000 gives ohm meters)
Range of Conductivity	0-3, 10, 30, 100, 300 mS/meter
Instrument Noise Level	Less than 0.2 mS/meter
Measurement Accuracy	±5% at 20 mS/meter
Measurement Precision	±2% of full scale deflection
Primary Field Source	Self-contained dipole transmitter
Sensor	Self-contained dipole receiver
Intercoil Spacing	Interchangeable 10 meters, 20 meters or 40 meters
Operating Frequency	6.4 kHz at 10 meter spacing 1.6 kHz at 20 meter spacing 0.4 kHz at 40 meter spacing
Operating Temperature Range	Operation to specifications within temperature range -40°C to +50°C
Power Supply	Transmitter: 8 disposable "D" cells Life: 20 hrs continuous duty-"NORMAL Life: 7 hrs continuous duty-"HIGH" Receiver: 8 disposable "C" cells Life: 20 hrs continuous
Reference Cable	Lightweight 2 wire shielded cable
Dimensions:	
Receiver Console	19.5 x 13.5 x 26 cm
Receiver Coil	63 cm
Transmitter Console	15 x 8 x 26 cm
Transmitter Coil	63 cm
Weights:	
Receiver Console	3.1 kg
Receiver Coil	5.6 kg
Transmitter Console	3.0 kg
Transmitter Coil	8.8 kg
Shipping Weight	50 kg

Sept. 1986./FBS


CAN H
C
12-3
A
B
BATTERY MONITOR METER


DECREASE
INCREASE
BATT
COIL SEPARATION
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1
0 .5 1 1.5 2 2.5 3
BATT
CONDUCTIVITY
MECHANICAL METER
ZERO ADJUSTMENT

EM 34-3 CABLE CONNECTION